F. M. Bullard

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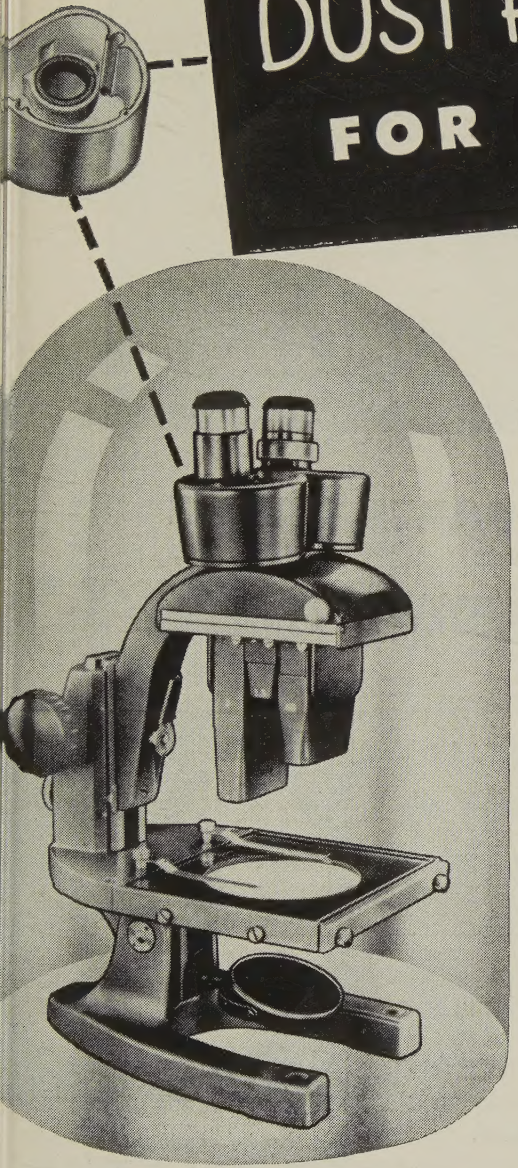

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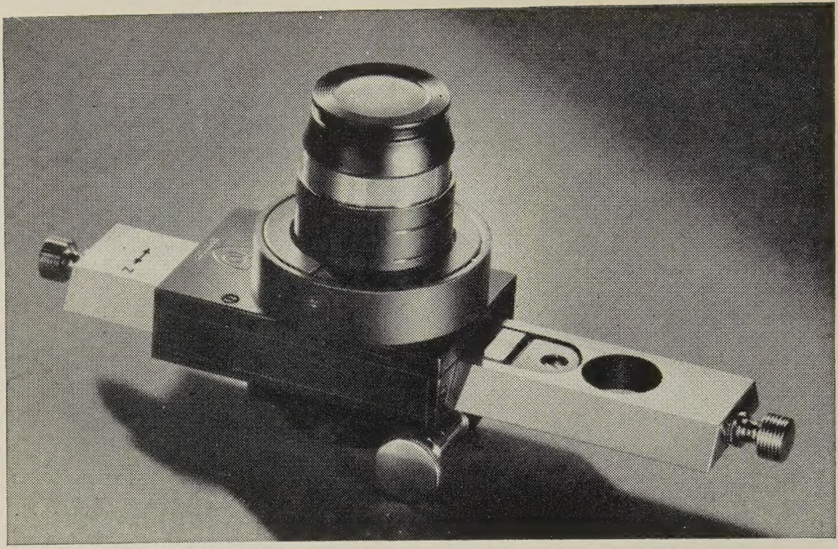

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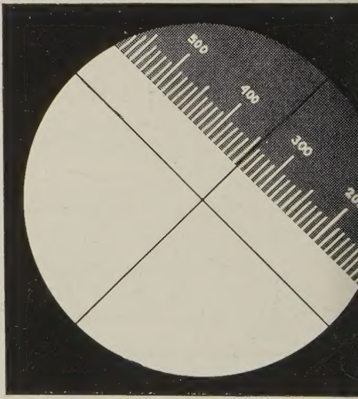

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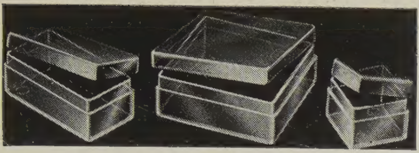

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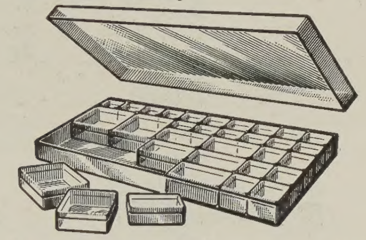

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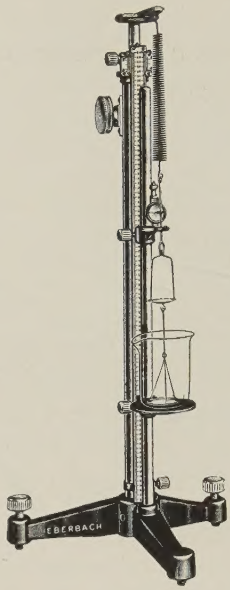

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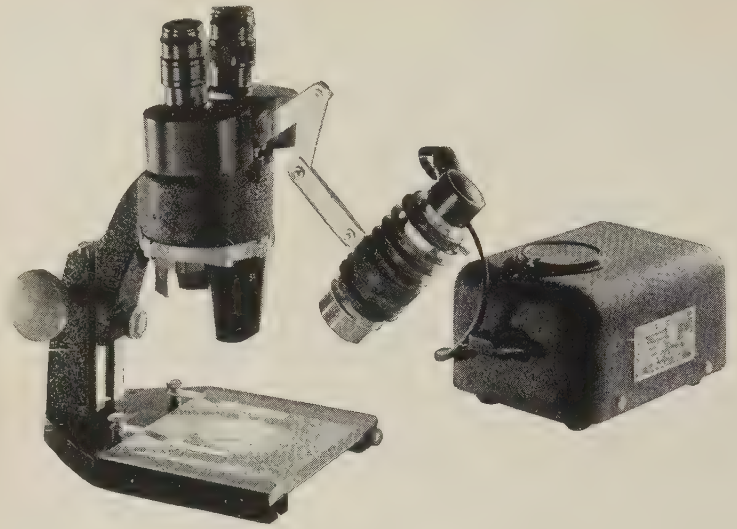

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Vol. 34 SEPTEMBER-OCTOBER, 1949 Nos. 9 and 10

CHEMICAL COMPOSITION AND OPTICAL PROPERTIES OF COMMON CLINOPYROXENES*

PART I.

H. H. HESS, *Princeton University, Princeton, New Jersey.*

ABSTRACT

A study of common clinopyroxenes is presented including 40 new chemical analyses. The optical properties of these pyroxenes have been systematically determined with somewhat better accuracy than normally attained. Techniques for determination of these properties are discussed and their probable accuracy estimated. The results of the study are graphically presented on a series of curves. The recalculation of the chemical analyses in terms of a theoretical pyroxene formula and the distribution of various ions in the pyroxene structure are discussed.

INTRODUCTION

The present investigation is aimed at determining the chemical composition and optical properties of such common clinopyroxenes as the petrologist is likely to find in the course of his work. Only rarely do common pyroxenes occur as good crystals easily separable from their containing rocks. Partly for this reason the literature contains a large proportion of analyses of peculiar and unusual varieties of pyroxenes. Of the several hundred chemical analyses of pyroxenes available many are old and the great majority of poor quality by present standards. Aside from inaccuracies of the actual chemical analyses, the purity of the material analyzed is open to question. Furthermore, only a small percentage of those analyzed are accompanied by descriptions of optical properties and the accuracy of the optical work may be doubtful. After a study of the literature very little material was found which could be used in the present study.

Optical property curves for clinopyroxenes have been published by Winchell (1923, 1935) and by Tomita (1934).† The latter were revised by Wager and Deer (1938). All of these compilations are to a large extent based on data from synthetic pyroxenes which appear in the works of Bowen, Schairer and Posnjak of the Carnegie Geophysical Laboratory. Use of the same data has been made by the present writer to obtain the general trend of the curves into those areas where natural clinopyroxenes do not occur or have not been found.

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* Princeton investigations of rock forming minerals, No. 4.

† Niggli (1943) has an exceedingly useful compilation of analyses of pyroxenes from igneous rocks with such optical data as was available.

ACKNOWLEDGMENTS

About three-quarters of this investigation was financed by research funds of the Department of Geology, Princeton University, and the remaining quarter by a grant from the Geological Society of America.

Almost all of the new chemical analyses are the work of Lee C. Peck and R. B. Ellestad. The skill and care with which these analyses have been made, in itself, represents a major contribution to the study of this mineral group. Acknowledgment is also due to the Rock Analysis Laboratory of the University of Minnesota, directed until recently by F. F. Grout, where Peck and Ellestad carried on their work. Without such a laboratory, this type of research work would not be possible.

Two samples for analysis from the Duluth area were obtained from F. F. Grout and one from A. N. Winchell. E. S. Larsen, Jr., supplied a small sample of the analyzed hedenbergite from the Percy Quadrangle, New Hampshire, previously described by Chapman and Williams (1935). H. E. Merwin gave the writer some of the hedenbergite analyzed by E.S. Shepherd (Wyckoff, Merwin and Washington, 1925). A.F. Hallimond sent the writer some of his analyzed "uniaxial augite" (1914).

A dozen of the Adirondack clinopyroxene analyses are a by-product of a study being carried on by A. F. Buddington and were kindly lent for the purposes of this study. These pyroxenes come from analyzed rocks representative of average rock types within given suites from that area and thus have a certain added geological significance. If, however, the purpose had been to pick the best material for pyroxene separations and analyses, some of these specimens would not have been chosen. Some of them are slightly altered and others have a minute amount of included impurities.

Five analyses of clinopyroxenes from skarn rocks are taken from the unpublished Ph.D. thesis of B. F. Leonard which deals with magnetite ore bodies of the Adirondacks. The writer is much indebted to Leonard for permission to use these analyses. Discussion of these analyses will be undertaken jointly with Leonard in a subsequent paper.

One augite analysis is from the unpublished thesis of Preston Hotz and another was contributed by A. W. Postel, both of which are gratefully acknowledged.

Thanks are due the U. S. Geological Survey for allowing the use of analysis number 37 by Norman Davidson and for the contributions to this work made by members of the Survey, Leonard, Hotz, and Postel.

The writer wishes to acknowledge his indebtedness to C. S. Hurlbut, C. Frondel, and B. F. Leonard for critical reading of the manuscript and for the many useful suggestions they made.

NOMENCLATURE

A nomenclature to describe common clinopyroxenes was outlined by the writer (1941) and is adhered to in this paper with the slight modifications indicated below. The term "endiopside," to describe clinopyroxenes with more magnesian and less calcic than diopside, should be dropped. The need for the term seems doubtful since pyroxenes of such a composition are rare; and since those that are found lie close to the augite field, they may as well be called augites with an appropriate adjectival modifier.

Benson (1944) suggested the term "subcalcic augite" to apply to that portion of the clinopyroxene composition field between augite ($Wo<25$) and pigeonite ($Wo>15$) which he correlated with optic angles of greater than 45° and less than 30°, respectively (Benson, Table IX). The writer would also adopt this term if pyroxenes are found which fall within the above composition range. Benson believes such pyroxenes are common, basing his estimate of Wo content on optic angle measurements. The present revision of the optic angle-composition curves indicates that the so-called subcalcic augites, which Benson was dealing with in his paper, all probably lie within his (Benson's) composition field of augite and are probably some 10%, or more, richer in Wo than he estimated. Though the writer believes that subcalcic augite is very rare or nonexistent, it may occur, inasmuch as the optic angle-composition curves are not always reliable. Minor constituents or peculiarities in conditions of crystallization may affect the size of 2V.

As a further modification it is proposed that the use of Wo (wollastonite), En (enstatite) and Fs (ferrosilite) be discontinued and Ca, Mg and Fe (% atoms) be substituted at the three corners of the composition diagram. This changes the diagram in no way, but eliminates the concept of mixtures of end member "molecules" which is inconsistent with present ideas on the actual occurrence of the constituents in the crystal structure. It is also recommended because it is convenient to add Fe^{+3} to Fe^{+2} in the optical property-composition curves since this gives a better approximation of the bulk composition than curves which neglect Fe^{+3}. Inasmuch as Fe^{+3} would not be present in theoretical Fs, it is an additional argument in favor of dropping Wo, En and Fs. Similarly the substitution of Al for Si, as well as other such replacements in the structure, is also better taken care of by eliminating the old molecule concept.

CHEMICAL CONSTITUTION AND THEORETICAL FORMULA OF CLINOPYROXENES

The structure of diopside was one of the first silicates to be worked out by *x*-ray methods (Warren and Lawrence, 1928) and its similarity to other clinopyroxenes was demonstrated by several investigators. The general formula for the pyroxene group suggested by Berman (1937) is here accepted with slight modification.

The formula for any pyroxene may be written as follows:

$(W)_{1-p}(X, Y)_{1+p}Z_2O_6$
$W = Ca^{+2}, Na^{+1}$
$X = Mg^{+2}, Fe^{+2}, Mn^{+2}, Ni^{+2}$
$Y = Al^{+3}, Fe^{+3}, Cr^{+3}, Ti^{+4}$
$Z = Si^{+4}, Al^{+3}$

Four such units would be required by the monoclinic cell and eight by the orthorhombic. In the above formula p would be zero or close to it for the diopside-hedenbergite or acmite-jadeite series and would be 1, or close to it, for the orthorhombic pyroxenes and pigeonites.

No doubt many other less common ions enter the pyroxene structure and probably some could enter in large amounts if the geological environment provided them. The above-mentioned ions are the only important ones in the rock-forming pyroxenes. Though the orthorhombic pyroxenes have relatively few of the ions of the W and Y groups such ions are present in small but appreciable amounts so that the formula as given is readily adaptable to either the orthorhombic or monoclinic members of the group. The pyroxene, spodumene, $LiAlSi_2O_6$, may be mentioned in passing though it plays no part in the present study since varieties intermediate between it and the rock-forming clinopyroxenes are not known.

The W, X and Y ions are in octahedral positions (coordination number 6) with respect to surrounding O^{-2} ions. In the Z group the Si^{+4} and the Al^{+3} ions are in tetrahedral positions (coordination number 4) with respect to surrounding O^{-2} ions. There is no evidence suggesting that Fe^{+3} or any other ion than Al^{+3} may substitute for Si^{+4} in appreciable amounts.

The simplest clinopyroxene would be of the type Ca (Mg, Fe) Si_2O_6. The substitution of Ni^{+2} for Mg^{+2} or Mn^{+2} for Fe^{+2} represents an easily understandable degree of variation. Where ions of different charge enter into the structure, these must be balanced electrically by other ions with compensatory charges. The distribution of various sorts of ions must fulfill the requirements set forth in Table 1 below as governed by the following rules: (1) The sum of the ionic charges in groups A and B of

Table 1 must add up to +12 to balance the −12 charge of the six O^{-2} ions. (2) *A* and *B* must each be represented by two ions to fill the required positions in the structure.

TABLE 1

	Distribution of electrical charge				Examples			
	A		B					
	W	X, Y	Z	O	W	X, Y	Z	O
(1)	+2	+2	+8	−12	Ca^{+2}	Mg^{+2}	$2Si^{+4}$	O
(2)	+1	+3	+8	−12	Na^{+1}	Fe^{+3}	$2Si^{+4}$	O
(3)	+2	+4	+6	−12	Ca^{+2}	Ti^{+4}	$2Al^{+3}$	O
(4)	+2	+3	+7	−12	Ca^{+2}	Al^{+3}	Al^{+3}, Si^{+4}	O

The above examples are not to be construed as end members of pyroxene series though (1) and (2) happen to be. Al can only substitute for Si to a limited extent in the structure. Since the Al^{+3} ion is much larger than the Si^{+4} ion, this substitution is probably limited by the degree to which the pyroxene structure may be stretched or distorted to accommodate the larger ion. The largest amount of Al substituting for Si in any pyroxene thus far analyzed is 27.6% in a pyroxene from a xenolith described by Dixon and Kennedy (1933). Very few analyses have been made showing Al replacing Si to an extent greater than 12%. Recalculation of a large number of analyses of titaniferous pyroxenes indicates that example (3) above is the normal manner by which the +4 charge of the Ti ion is accommodated. The only other way by which it might be done is by substituting two monovalent ions such as Na for two divalent ions such as Ca for each Ti entering the structure. Search for analyses to substantiate such a relationship proved negative. Neptunite of the pyroxenoid group, however, might have such combination.

EXPLANATION OF CHEMICAL ANALYSIS TABLES

In handling the chemical analyses the weight per cents of the oxides were first converted to molecular ratios and then to ratios of ions. To save space in the tables the molecular ratios column was omitted since it could easily be derived from the atomic ratios by inspection if there were need therefor. The ions with +2 charge can readily be combined in a 2:2 ratio with the Si ions to form pyroxene molecules. However, the +1, +3 and +4 ions must be so distributed that the charges compensate and the correct proportion of ions is obtained in each group as explained above. This operation is performed in the tables and is accomplished in the following manner: (1) Na ions are combined with Cr ions if present to form $NaCrSi_2O_6$; (2) Remaining Na ions are combined with Fe^{+3} to form $NaFeSi_2O_6$; (3) Na ions remaining after the above steps are combined similarly with Al ions; (4) For each Ti ion two Al ions are placed in the Z group substituting for Si; (5) If Cr ions are in excess of Na ions and are still to be accounted for, each Cr ion is combined with one Al ion placed in the Z group; (6) After these five steps some Al is almost invariably present. This is split into two equal parts one going into the Y group and one into the Z group. If the chemical analysis is accurate and the material analyzed pure, the total number of ions in the Z group (Si+Al) will come within about 2 per cent of equaling the total number of ions in the $W+X+Y$ groups, and these will be in the ratio of 2:2:6 as compared to the total number of O ions. This is tested by dividing the total O ions by six and dividing the resulting figure into the number of ions in the Z group and into the sum of the ions in the $W+X+Y$ groups. The result of these two divisions should equal $2.00 \pm .02$ in a completely satisfactory analysis. The common practice in the literature of splitting the Al between the Z group and the $W+X+Y$ groups in that proportion will make their ratio 2:2 if possible, conveniently compensates error in the analysis and is contrary to the rule which requires balancing of electrical charge.

Since the optical property curves are based on the ratio of Ca:Mg:Fe atoms, the three major variables in the pyroxenes under consideration, this ratio recalculated to 100% is given at the bottom of each table. In this calculation Fe^{+2} and Fe^{+3} are added together plus the small amount of Mn normally present. If Ni is present it is added to the Mg. The per cent Al replacing Si in the Z group is also indicated at the bottom of the table since this represents the fourth most important variable.

In the recalculation of the analyses H_2O is omitted since its constituents probably do not enter the pyroxene structure. In the few cases where H_2O is present in appreciable amount, it probably represents an alteration product and is best neglected in the recalculation.

SEPARATIONS

The major part of all separations was performed with the Frantz Isodynamic Magnetic Separator. In those cases where a completely pure separate was not obtained, heavy liquids were resorted to for final purification. If this was not successful the sample was discarded as being unsatisfactory.

Rocks containing the pyroxene to be separated were crushed to pass through a 100 mesh sieve or, for finer grained rocks, a 200 mesh sieve. The fines and adhering dust were removed by washing and decanting. In a few cases limonite stain or adhering grains of chlorite or serpentine were removed by boiling for ten minutes in dilute acid (HCl). Magnetite, or grains including magnetite, and iron filings from the mortar were removed with an Alnico bar magnet before introducing the sample into the magnetic separator.

In slowly cooled rocks where crystals exhibit a minimum amount of zoning magnetic separations are as a rule excellent. In hypersthene gabbros, for example, the pyroxenes can be separated cleanly from the rock and the hypersthene and augite cleanly from one another. In the more quickly cooled diabases, on the other hand, it is exceedingly difficult to separate the augite from the pigeonite since both of these minerals are zoned and their ranges of magnetic susceptibility overlap almost completely. Since the density ranges of these two minerals also overlap, the best that could be done was to produce an augite and a pigeonite concentrate, analyze both, and from the proportions present in each sample calculate the compositions of the pure minerals.

DETERMINATION OF PROPERTIES

About two weeks were spent on each of the analyzed pyroxenes, determining the various optical properties. A considerable portion of this time was used in attempts to develop better or easier methods of measurement. In the work thus far completed the accuracy of certain measurements could be improved, but it did not seem warranted to hold up publication any longer to effect further refinements. In many cases the measurements of $Z \wedge c$ are unsatisfactory and no reliable method was found for determining this value for many of the samples. Similarly, density determinations on powders showed so large a degree of fluctuation on repeated measurements that most of them were discarded as valueless. Measurements of dispersion gave promise of supplying usable criteria to distinguish the presence of, and possibly the amounts of, certain minor constituents but this study has not yet been completed. Observations on measurements of specific properties are summarized below.

(*a*) *Indices of refraction.*

All pyroxenes when crushed exhibit a small to moderate percentage of pinacoidal parting tablets. For all clinopyroxenes, except pigeonites, the {100} parting tablets were used to determine the Y index accurately. These are easily recognized with practice and can be spotted quickly from among the large number of grains on the slide. They have low birefrigence since an optic axis emerges from them at approximately 20° from the vertical. If bounded by cleavages, or other partings, they exhibit parallel extinction. The orientation of the grain is checked in convergent light. An off-center optic axis figure should result. The stage is rotated until the isogyre is east-west. If it exactly splits the field in two then the optic plane is vertical and Y, the optic normal, is north-south. The grain is now in position to determine the Y index. For pigeonites with the optic plane ⊥ {010} it is necessary to use the {010} parting tablets and determine Y or Z, checking orientation against the observation of a centered Bx_0 figure, or either the {100} or {001} parting tablets and determine X.

Though {110} cleavage fragments are very common they give unreliable results since exact orientation cannot be checked by the interference figure, and many of them are tilted an unknown amount from the {110} plane.

The observations were made in white light and checked when close with a sodium vapor lamp. The light was passed through an infra-red filter to remove heat since errors resulting from not knowing the temperature of the immersion liquid are the largest potential source of error. Temperatures were checked by swinging a thermometer into position under the objective before and after observation.

Ordinary immersion methods were used with a closely spaced and carefully calibrated set of index liquids. Observations were made at different times on the same day or on different days when room temperature had changed sufficiently to split the spacing between index liquids. The index of the grain to be determined was bracketed between two oils about .001 apart. The normal accuracy for index determinations is estimated to be ±.0005 except for material of variable composition. For the latter it is ±.001.

It was found to be both easier and more accurate to determine the other two indices by calculations from birefringence and optic angle determinations described below. For this purpose Wright's curve was used (1911, plate 9).

(*b*) *Birefringence.*

Birefringence was determined with a Berek compensator on specially prepared slides. These were made as follows: A small amount of the mineral was mixed with an equal amount of fine quartz sand. A bakelite mount such as commonly used for polished section work was then made in a press (150° C. and 4000 lbs./sq. in.).* One end of the mount cylinder was ground on a very flat steel lap with fine abrasive so that a semi-polished, very flat surface resulted. This surface was cemented to a glass slide and ground to .06 mm. thickness and then flattened and cut to ±.04 mm. on the same steel lap as mentioned above. This gave two very flat surfaces which were almost if not quite parallel. Thicknesses of four or five quartz grains surrounding the pyroxene to be measured were then determined by measuring path difference with the Berek compensator after the *c* axis had been made horizontal on the universal stage. Path difference in the quartz was converted directly to thickness by means of a curve. The thickness value was then multiplied by the cosine of angle of tilt of the stage corrected for indices of refraction of quartz and the hemispheres thus giving true thickness of the slide at the point of observation. The results give the thickness of the pyroxene grain to approximately ±.0001 mm. and birefringence of a pyroxene grain can ordinarily be measured to ±.0002. This is more accurate and much less tedious than measuring the other indices of refraction. A number of the pyroxenes measured had somewhat variable birefringence necessitating from five to twenty observations to obtain a satisfactory average for the sample.

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* Balsam mounts were not very satisfactory since it proved difficult to get a very flat surface on them. This is attributed to the relative softness of balsam.

In choosing pyroxene grains for measurement only those were selected which happened to have the optic normal nearly vertical in the slide so that there would be only a small amount of correction for tilt. A fair number of such grains can be found since they represent the {010} parting tablets which were lying on this face when the mount was made.

The Berek compensator is of little practical use on an ordinary thin section because the thickness can normally not be measured within an accuracy of better than ±10%. Ordinarily thin sections vary rather erratically in thickness from grain to grain as well as across the slide, as a whole, so that even if they contain quartz on which Berek measurements can be made, the accuracy nevertheless is low. Measuring thickness by various focusing methods commonly involves errors from 10% to 40%. Unless special slides are made the Berek compensator gives little better accuracy than merely estimating birefringence by observing the interference color.

(*c*) *Optic Angle.*

All optic angle measurements were made on the universal stage on grains which had Bx_a near vertical and by direct rotation from one optic axis to the other. It appears that this observation for optic angles ranging from 20° to 60° is more accurate than most authors state. The accuracy after index corrections is certainly better than ±0.5° and probably better than ±0.3° judging from the variations obtained by repeated measurements on the same grain, or on numerous grains of uniform material. On the other hand, measurements of the optic angle by rotating from one optic axis to a bisectrix are apparently less accurate than one would suppose from the literature. Errors of five degrees are fairly common. In fact it appears that the orientation of a grain on the universal stage to bring *X*, *Y* or *Z* to the vertical position cannot ordinarily be done with the accuracy usually attributed to such orientation procedures (see Turner, 1942).

(*d*) *Dispersion.*

Dispersion of the optic axes was noted and recorded during the optic angle measurements. It is quite evident upon rotation of the stage through an optic axis even when not observable at all in the interference figure. Where the dispersion was just perceptible it was called weak, where quite obvious but too small to measure accurately, it was called moderate, and where greater than approximately 0.5°, it was called strong. In most cases the dispersion is inclined. The optic axis emerging in {001} not far from the *c* axis is labelled "B" and the other emerging in {100} is labeled "A". (Fig. 1A) The dispersion on each axis is given.

The dispersion of the indices of refraction, birefringence and $Z\wedge c$ have not been measured but represent a fruitful field for further investigation.

(e) $Z\wedge c$.

Since most common clinopyroxenes have an extinction angle, $Z\wedge c$, between 40° and 46°, an accuracy of at least ±1° is necessary if the observations are to have any determinative value. Even so their value is comparatively small. Reasonably reliable values can be obtained on twinned crystals by following a procedure such as suggested by Nemoto (1938) and Turner (1940). Analogous methods were used by the writer and are described below. On untwinned clinopyroxene, as a rule, the value cannot be determined with the required accuracy.

To escape the comparatively large possible errors in bringing X or Z to coincidence with the microscope axis, these positions were, as a rule, not measured nor were such physical discontinuities as cleavages or twinning planes. Choosing only twinned crystals which had their optic planes nearly vertical (±20°) by rotation about Y $(=b)$, the angles between two optic axes of one twin and one of the second twin were measured as well as the positions equivalent to the pole of {100} and the direction of the *c* axis. The latter two positions can be found by rotation about Y to the point where the birefringence of the twins exactly matches. Thus the angles $A_1\wedge B_1(=2V)$, $B_1\wedge B_2$ or $A_1\wedge A_2$ and either the angles $A_1\wedge\{100\}$, $A_2\wedge\{100\}$ or $B_1\wedge c$, $B_2\wedge c$ can be measured on almost any such favorably oriented grain. In the special case where Bx_a is vertical, the angles $B_1\wedge c$, $A_1\wedge B_1$ and $A_1\wedge\{100\}$ can be observed. Three of these angles will ordinarily require tilts of 0°–45° and the one or perhaps two other angles will require tilts of 45°–55°. Higher tilts result in unacceptable errors particularly if the index of the mineral is greatly different than the index of the glass hemispheres. Those angles between 45° and 55° should be marked as having lower accuracy than those below 45°. Normally about ten such twinned crystals were measured and the results averaged giving greater weight to the angles with lower tilt. From such a series of measurements all angles in the plane ||{100} can be observed or calculated with accuracy estimated to be better than 1° and probably good to ±0.5°. $Z \wedge c$ and 2V are thus determined simultaneously.

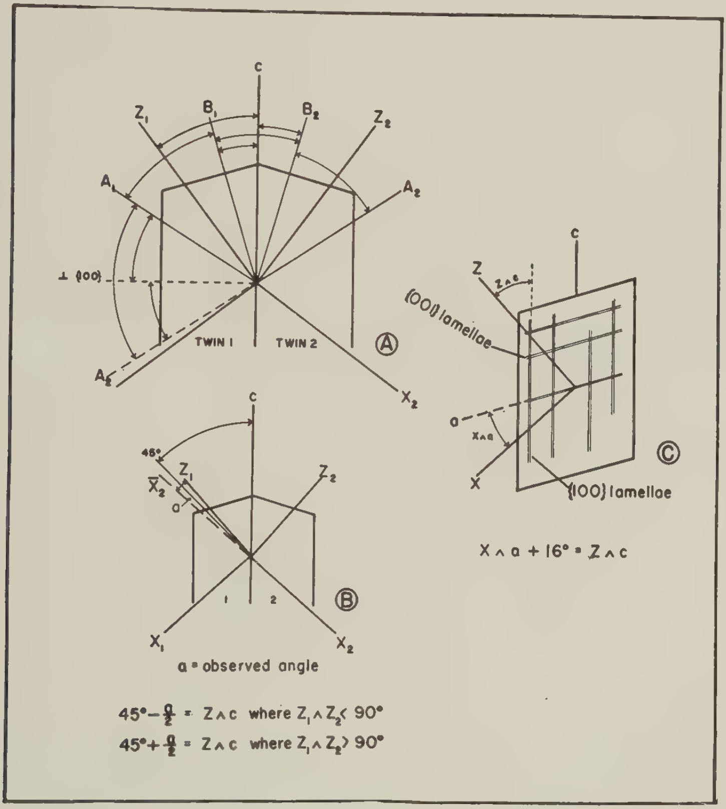

FIG. 1. Measurement of $Z \wedge c$.

In powders twinned {010} parting tablets can be found in rare cases. In such cases $Z \wedge c$ can be determined fairly well by measuring $Z_1 \wedge X_2$ as shown in Fig. 1B. This angle is normally less than 10°.

In untwinned clinopyroxenes exhibiting very fine, sharp exsolution lamellae of orthopyroxene parallel to either {100} or {001}, the angle $Z \wedge c$ or $X \wedge a$ may be measured on {010} parting tablets in powders

(Fig. 1C). This is not as satisfactory as the other two methods suggested above.

(*f*) *Pleochroism.*

The absorption indicatrix does not coincide with the optical indicatrix (X, Y, Z) in most clinopyroxenes. The colors observed can more readily be related to the directions paralleling the b and c axes and the direction at right angles to the bc plane. It is evident from the analyses that the color of those pyroxenes herein described may be directly related to the Fe^{+3} ion (predominantly greens) and to Ti (purplish tints). No other ions have thus far been identified as affecting the transmitted color of clinopyroxenes either by themselves or in conjunction with the above. Where no data are given on pleochroism the mineral appeared to be virtually colorless in thin section. Faintly colored specimens were examined in relatively thick sections or grains to determine the pleochroism.

(*g*) *Density.*

Accurate density determinations on mineral grains are difficult to make. The numerous pitfalls are adequately pointed out by Mason (1944). The most successful measurements were made with the Berman balance. This has the great advantage of permitting rapid measurements so that in an hour or two a number of observations can be made (10 to 15 minutes per grain). In this manner the results can be compared, extremes discarded, and a group of fairly consistent values averaged. It is assumed that the aberrant values are grains with unseen cavities or inclusions. Unfortunately, this method is only applicable when pure grains of at least 10 milligrams can be obtained. It is preferable to use a 20–25 milligram sample*.

Toluene was used in the Berman balance determinations. The accuracy is thought to be better than ±0.01. All observations were made at room temperature (density of toluene at that temperature being used in the calculation) and are uncorrected for atmospheric pressure. (Plate IX)

A large number of pycnometer determinations on powders were made but these are considered to be too unreliable to report. Some determinations were made at the Rock Analysis Laboratory on Buddington's Adirondack pyroxenes presumably by pycnometer and these are attributed to the Laboratory in the tables. The writer has no basis for judging their accuracy.

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* It seems likely that if further experimentation were undertaken on powders that a method using a rather large volume of heavy liquid would be the most satisfactory for routine determinations. Large volume of liquid would minimize the errors resulting from measuring the volume of the liquid and weighing it to obtain its density. This might be coupled with calibration of the liquid for thermal expansion and density comparison to the powders in a cell with variable controlled temperature thereby eliminating the need for diluting the liquid and having to measure its density along with each sample determined. Mason suggests measuring volume by displacing a gas, a method which also has promise of greater accuracy than current methods.

EXPLANATION OF OPTICAL PROPERTY CURVES

The coordinates of the curves are in per cents of atoms of Ca, Mg and total Fe. These ions plus their associated Si and O make up the great bulk of the pyroxenes under consideration. There are, however, five or six weight per cents of other metallic oxides normally present in the chemical analyses. As a rule, these other constituents are present in fairly uniform proportions in naturally occurring Ca-Mg-Fe clinopyroxenes. It is assumed in drawing the curves that the following amounts of these other constituents are present: Al_2O_3 3%; Fe_2O_3* 1.5%; Na_2O 0.4%; TiO_2 0.4%; MnO 0.3% but higher in more ferriferous samples; Cr_2O_3† 1.1% in highly magnesian augites of igneous rocks but negligible after Fe atoms reach 13% (of total Ca+Mg+Fe); other oxides negligible amounts. If these minor constituents are present in considerably different amounts than assumed, this can in most cases be recognized by failure

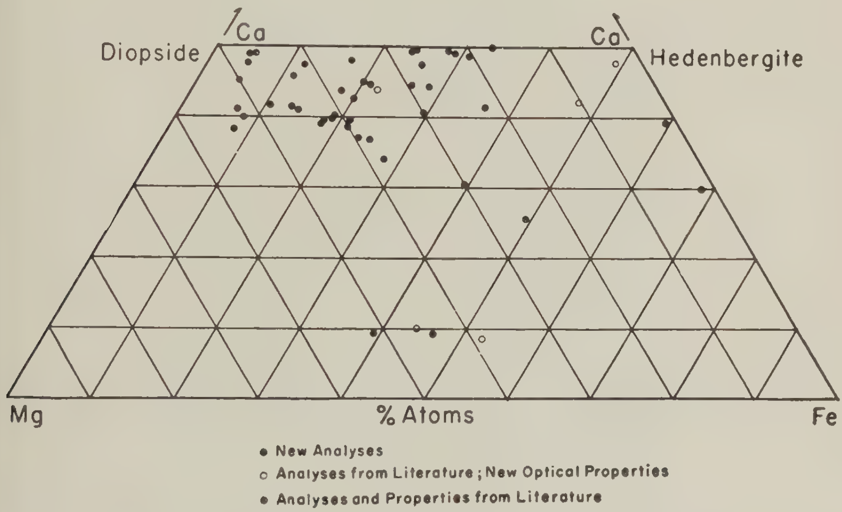

FIG. 2

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* Though the Fe^{+3} ions are included in the total Fe of the curves, the effect of Fe^{+3} on optical properties is not exactly the same as Fe^{+2}, so it has to be dealt with in the same way as other minor constituents.

† Cr_2O_3 content is taken care of by an extra set of dashed curves for Mg-rich augites in Plates I, II and III.

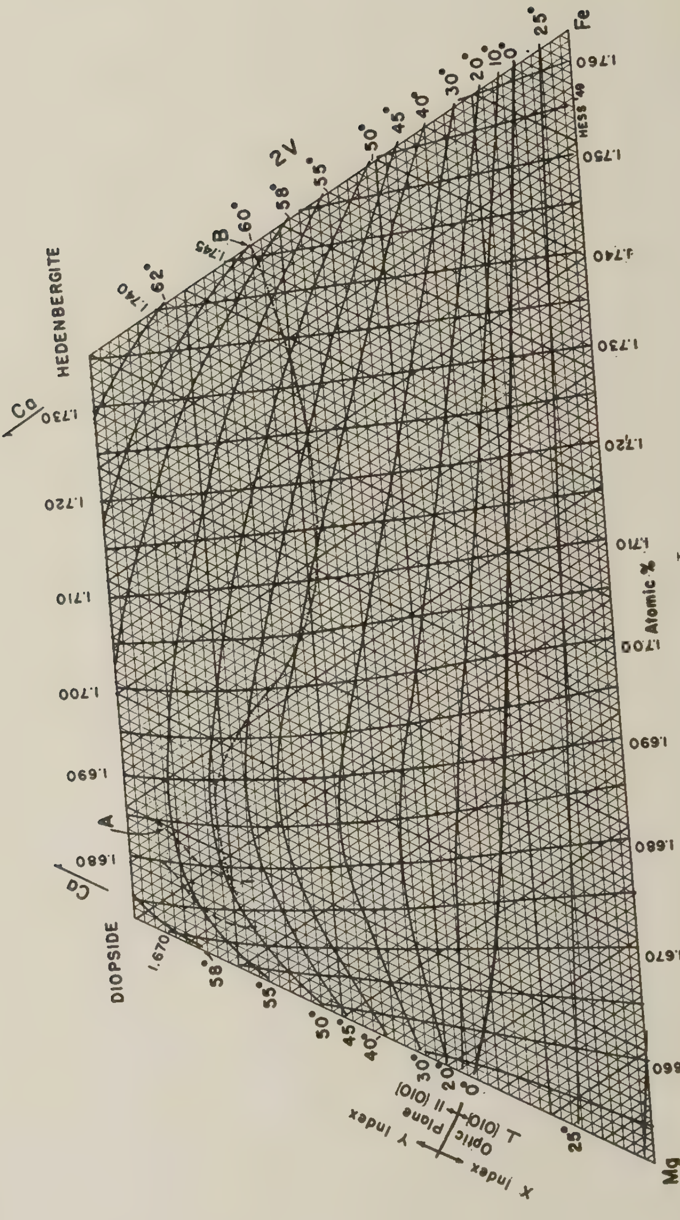
HEDENBERGITE
DIOPSIDE
Ca
Ca
Fe
Mg
2V
A
B
1.660
1.670
1.680
1.690
1.700
1.710
1.720
1.730
1.740
1.745
1.750
1.760
62°
60°
58°
55°
50°
45°
40°
30°
20°
10°
0°
25°
HESS 49
Atomic %
X Index
Y Index
Optic Plane
⊥ (010)
∥ (010)

PLATE I

of the optical properties to group together in such a manner that they fit the curves. In a succeeeding part of this series of papers the specific effects on optical properties of each of the above mentioned minor oxides will be evaluated.

Two end members of the curves, diopside and hedenbergite, tend to occur as relatively pure Ca-Mg or Ca-Fe clinopyroxenes, though the intermediate varieties rarely if ever do. The optical property curves take into account this normal decrease in "impurities" upon approaching these two corners of the diagrams.

The distribution of analyses on which the curves are based is shown in Fig. 2. Since there are no natural clinopyroxenes along the side of the diagram from clinoenstatite to a point quite close to diopside, the terminations of the curves along this side are taken from the synthetic pyroxenes described by Bowen and Schairer (1935). Similarly use is made of the synthetics from hedenbergite towards ferrosilite by Bowen, Schairer, and Posnjak (1933). The curves are most reliable for those areas where natural clinopyroxenes are commonest such as, for example, from diopside to $Ca_{38}Mg_{40}Fe_{22}$ or in the salite area. Conversely, they are least reliable where natural clinopyroxenes are very rare or do not exist, so that the writer does not feel too much concern for most of the area where the data are poor. One area, however, does cause him concern and that is in the region from ferroaugite with 30% Ca toward hedenbergite. These ferroaugites are not too rare for they occur in ferrogabbros, syenites, and some granites as well as probably in the ground mass of ferriferous lavas. The curves here depend very largely on only two analyses of Skaergaard pyroxenes (Wager and Deer, 1939).

Plate I presents curves for variation of the optic angle with composition. It also shows curves for the Y index of refraction for the area above $2V=0°$ and the X index for the area below $2V=0$. The reasons for shifting from Y to X index upon crossing $2V=0°$ are: (1) The X and Y curves come together at $2V=0°$ so that Y of the augite field is continued in a smooth curve as X in the pigeonite field thus making this combination easier to construct than a broken curve; and (2) Y of the augite field and X of the pigeonite field are respectively the easiest indices to determine accurately in each case. Thus this becomes not only the simplest but also the most useful combination to present on one diagram.

At "A" near the upper left hand corner of Plate I are two dashed lines diverging at a sharp angle from the Y index curves of this area. These dashed lines in this Plate and Plates II and III should be used for *igneous rock* clinopyroxenes rather than the solid lines if the determined optic angle and indices indicate pyroxenes falling within this area. The cause of this divergence of the index of refraction in igneous pyroxenes is related to the rapid increase of Cr^{+3} with high Mg which seems to occur in practically every case and in a regular manner. Cr_2O_3 amounts to 1.1% when Fe is 7%* and decreases abruptly to almost zero at Fe equal to 13%*, thus the 1.69 *Y* curve is not at all displaced by this effect. Further consideration will be given to this point in the part of this series of papers which will deal with clinopyroxenes of gabbros, norites, peridotites, etc.

"B" on the center right-hand side of Plate I indicates a dotted curve representing the normal trend of crystallization of clinopyroxenes from common mafic magmas as previously outlined by the writer (1941). It is often convenient to estimate the composition of such a clinopyroxene rapidly by determining the *Y* index and noting its point of intersection with the crystallization curve. It is also a convenient check on compositions inferred from 2V and *Y* index.

The optic angle curves were drawn by first making rough curves to fit 30 analyzed clinopyroxenes and using a smoothed curve for the synthetic pyroxenes from clinoenstatite to diopside. These rough curves were then smoothed to make an even distribution of the variation of 2V over the field. The smooth curves were then compared to the points for analyzed pyroxenes with the following results. The maximum departure for any one point from the curves was 4°. The average departure with respect to sign was $-1.25°$ and without regard to sign 1.5°. Ninety-four per cent of the observed values depart from the curves by 3° or less, 80% by 2° or less, and 60% by 1° or less. The distribution of points over those areas where natural clinopyroxenes occur is good except in the ferroaugite area, though even in this area the curves cannot depart far from being correct unless an abrupt change in slope of the general family of curves takes place which seems unlikely.

Where exsolution of lamellae of hypersthene has taken place in augites (or any clinopyroxenes) the optic angle of the host material will increase by about 3°. Thus if the bulk composition of the host plus lamellae is desired, about 3° should be subtracted from the observed value before entering the curves.

Plate II presents the *Z* index of refraction, and Plate III the *X* index above $2V=0°$ and *Y* index below $2V=0°$. These curves were calculated by superimposing the birefringence curves (Plate III) on Plate I, and calculating the remaining two indices of refraction by use of Wright's curves relating optic angle, birefringence and partial birefringence. While these curves are not strictly correct, the errors amount to only about 2 in the fourth decimal place as rule for the birefringences, indices, and

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* Of total number of Ca+Mg+Fe ions.

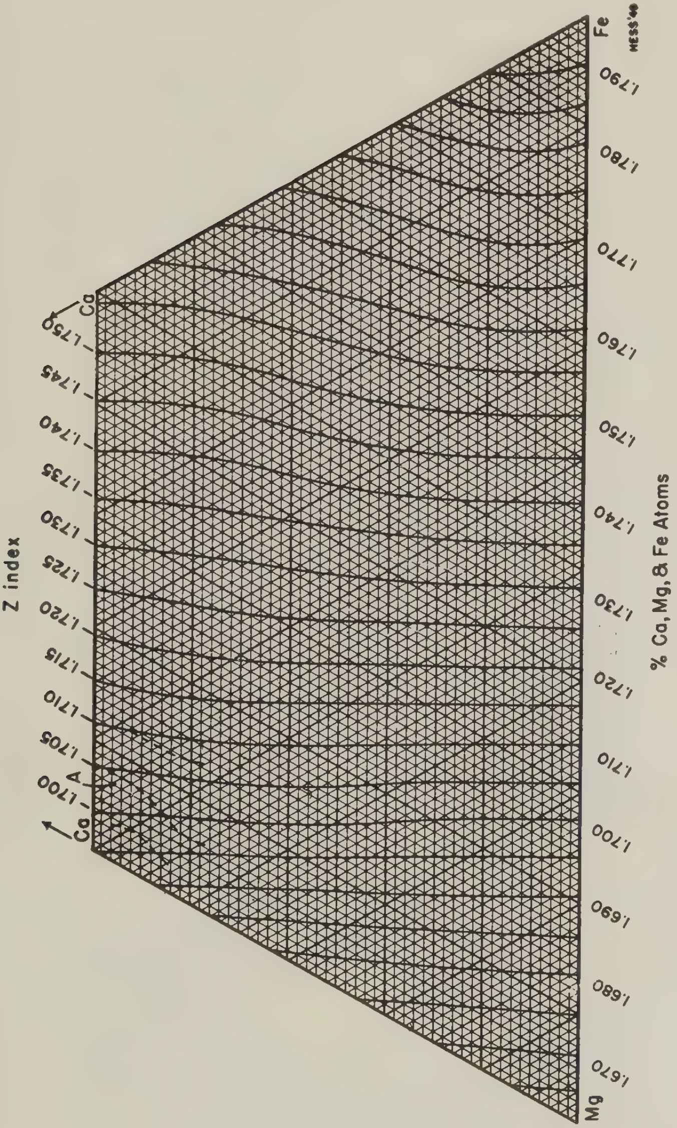

Z index
Ca
1.700
A
1.705
1.710
1.715
1.720
1.725
1.730
1.735
1.740
1.745
1.750
Ca
Mg
1.670
1.680
1.690
1.700
1.710
1.720
1.730
1.740
1.750
1.760
1.770
1.780
1.790
Fe
HESS'49
% Ca, Mg, & Fe Atoms

PLATE II

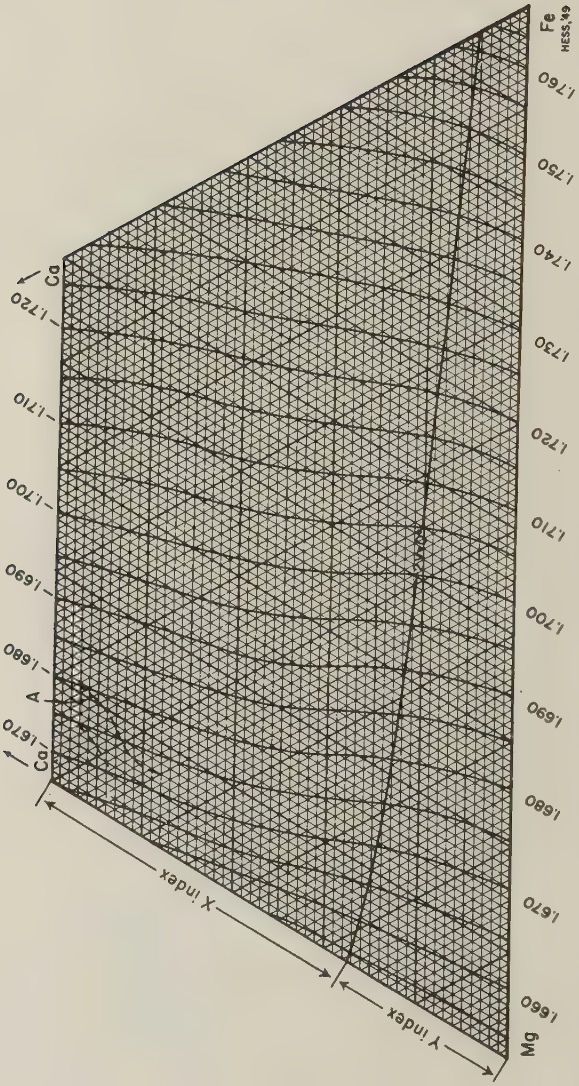

Ca
1.720
1.710
1.700
1.690
1.680
A
1.670
Ca
X index
Y index
Mg
1.660
1.670
1.680
1.690
1.700
1.710
1.720
1.730
1.740
1.750
1.760
Fe
HESS,'49
% Ca, Mg, & Fe Atoms

PLATE III

optical angles here encountered (see Larsen and Berman 1934, p. 6–7). Considering the larger uncertainty in the measured values, this error is acceptable.

Plate IV gives the birefringence variation with changes in Ca, Mg, and Fe concentration. Birefringence is markedly decreased by Al substituting for Si in the *Z* group. After determining the composition of the clinopyroxene on Plate I, a comparison of observed vs. normal birefringence as given on Plate IV will indicate deviations in Al concentration from the assumed amount. Exsolution of hypersthene lamellae from augites will generally increase the birefringence of the host material by a small but appreciable amount. Several of the analyzed titanaugites show birefringence about .0015 above the normal values indicated by the curves. Other titanaugites are normal. It has not been possible thus far to correlate this abnormality with variation in the amount of Ti or amount of any of the minor constituents. Possibly it is related to conditions of crystallization.

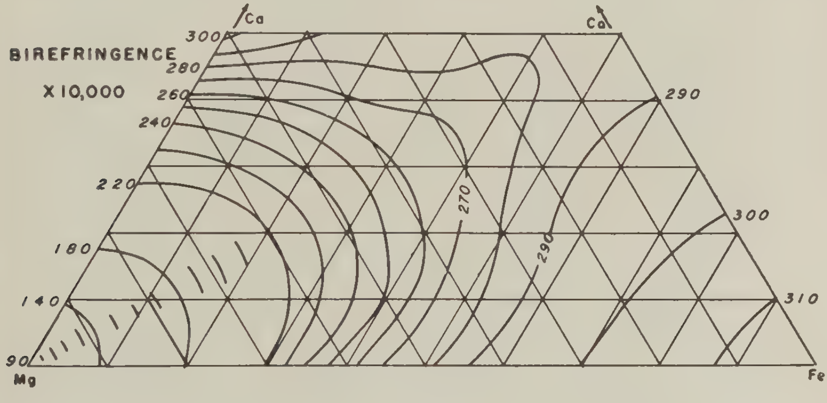


Plate IV

In succeeding parts of this study the following subjects will be considered: Skarn clinopyroxenes from the Adirondacks (with B. F. Leonard). The diopside-hedenbergite series and related clinopyroxenes. Augites and pigeonites from crystallization of basaltic magmas. The effects Ti^{+4}, Al^{+3}, Fe^{+3}, Cr^{+3}, Mn^{+2}, Na^{+1} on optical properties. The optical property curves for skarn pyroxenes (Plate V), the diopside hedenbergite series (Plate VI), Mg-rich igneous augites (Plate VII), and pigeonites (Plate VIII) are all included in this paper in order to present the main body of the descriptive material as one unit. Discussion of these plates will be undertaken in the subsequent papers.

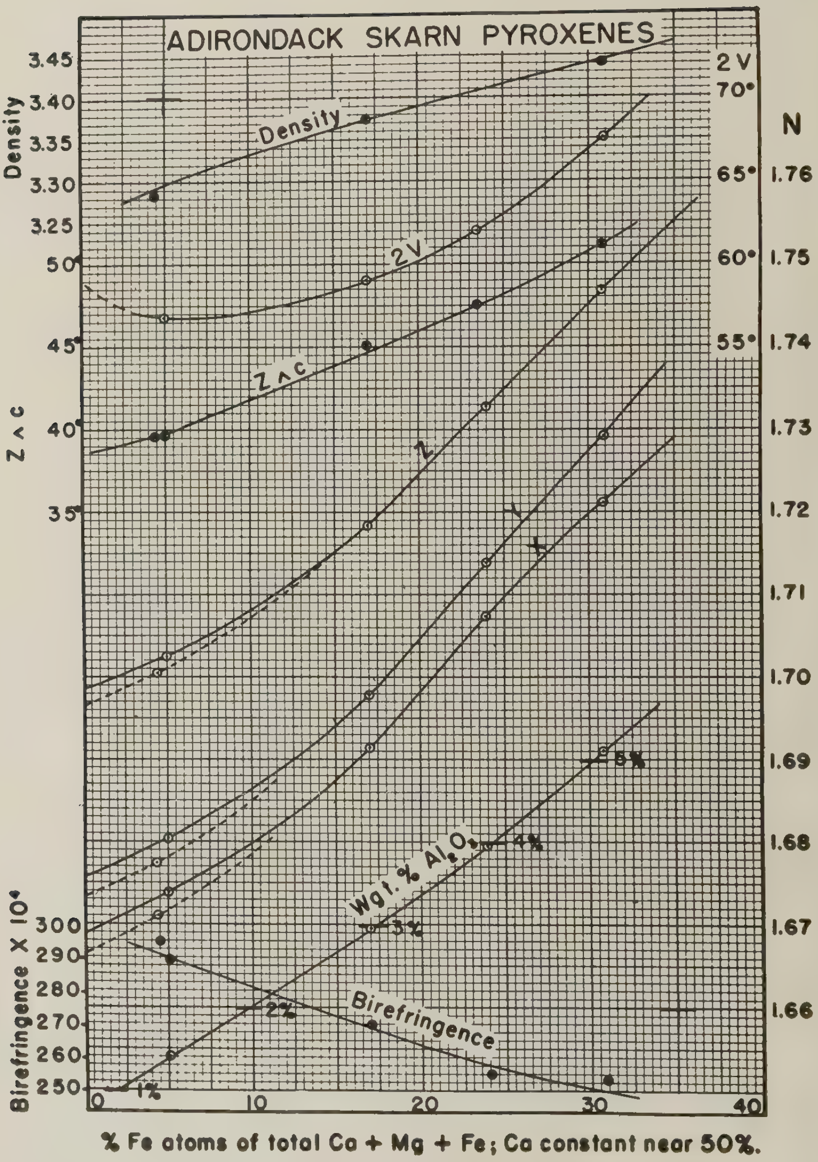

ADIRONDACK SKARN PYROXENES
Density
3.45
3.40
3.35
3.30
3.25
Z ∧ c
50°
45°
40°
35°
2 V
70°
65°
60°
55°
N
1.76
1.75
1.74
1.73
1.72
1.71
1.70
1.69
1.68
1.67
1.66
Density
2V
Z ∧ c
Z
Y
X
Wgt. % Al₂O₃
1%
2%
3%
4%
5%
Birefringence
Birefringence X 10⁴
300
290
280
270
260
250
0
10
20
30
40
% Fe atoms of total Ca + Mg + Fe; Ca constant near 50%.

PLATE V

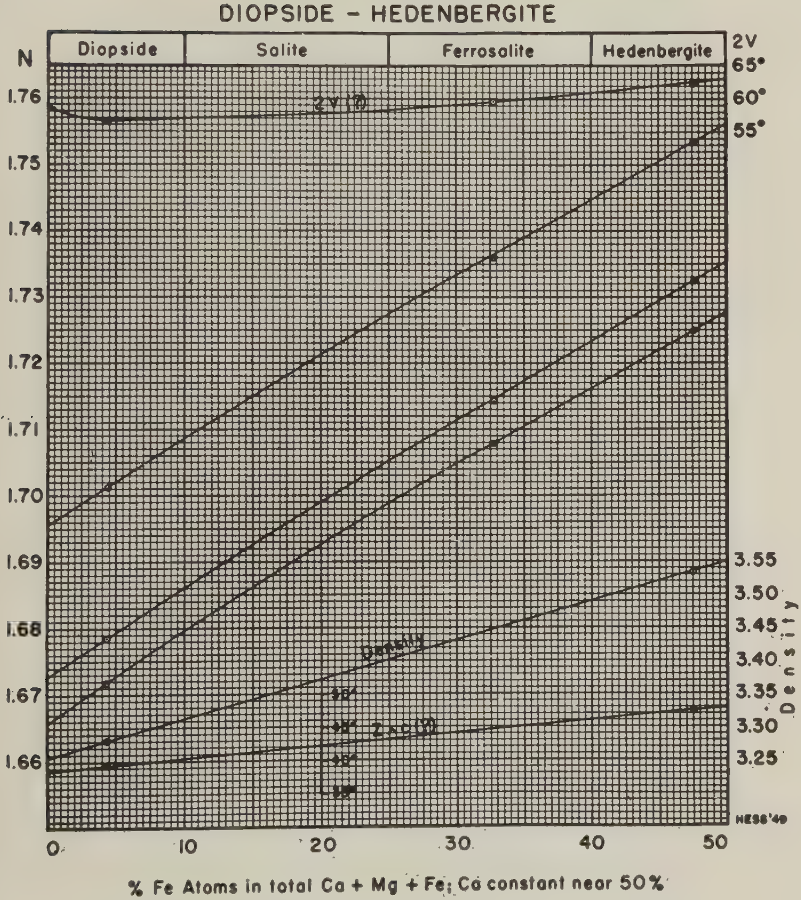

DIOPSIDE - HEDENBERGITE
Diopside
Salite
Ferrosalite
Hedenbergite
N
1.76
1.75
1.74
1.73
1.72
1.71
1.70
1.69
1.68
1.67
1.66
2V
65°
60°
55°
2V (?)
Density
2 Λ c (?)
3.55
3.50
3.45
3.40
3.35
3.30
3.25
Density
HESS'49
0
10
20
30
40
50
% Fe Atoms in total Ca + Mg + Fe; Ca constant near 50%

Plate VI

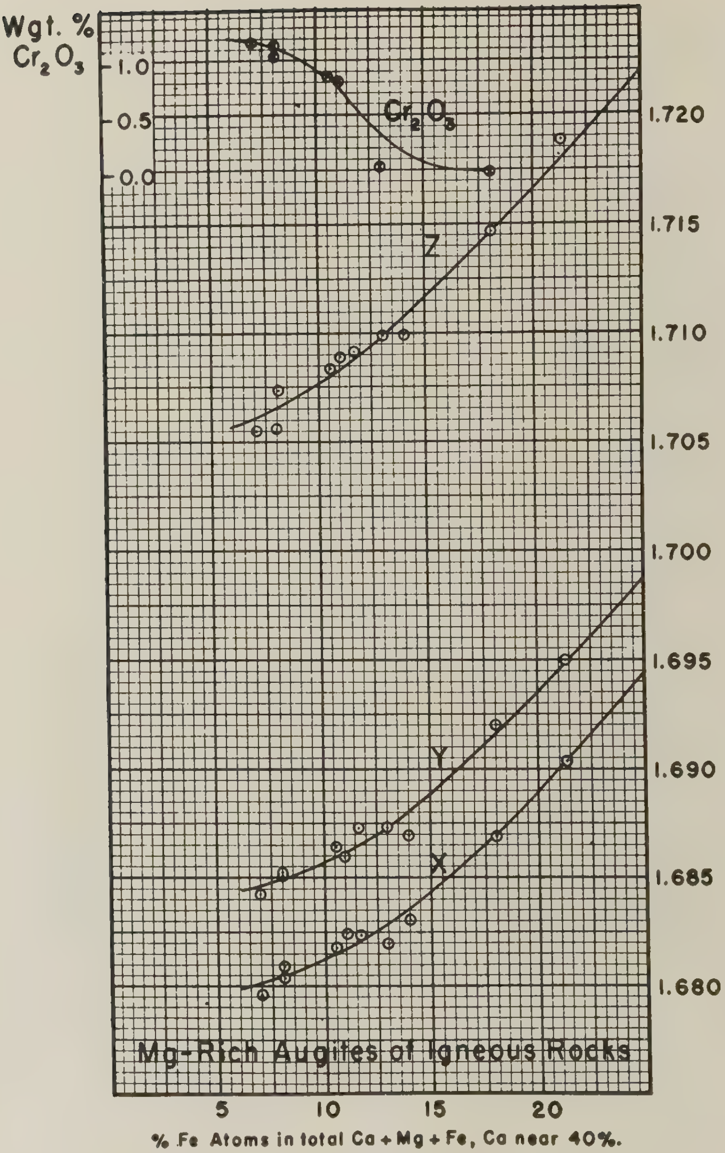

Wgt. %
Cr_2O_3
1.0
0.5
0.0
Cr_2O_3
Z
Y
X
1.720
1.715
1.710
1.705
1.700
1.695
1.690
1.685
1.680
Mg-Rich Augites of Igneous Rocks
5
10
15
20
% Fe Atoms in total Ca + Mg + Fe, Ca near 40%.

PLATE VII

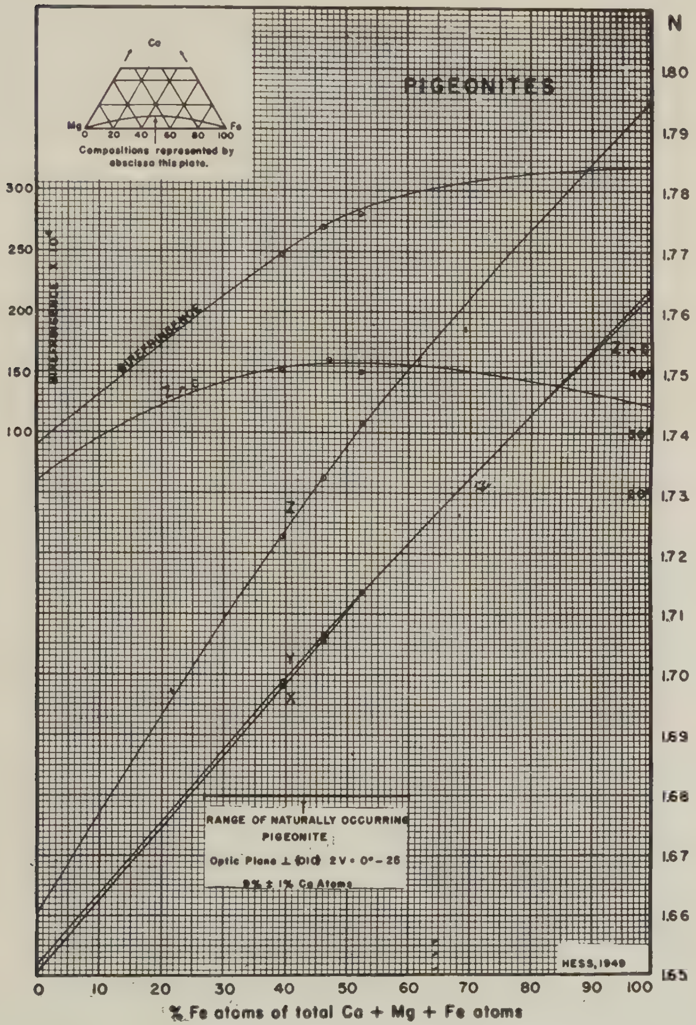


PLATE VIII

REFERENCES

BENSON, W. N. (1944), Basic igneous rocks of Eastern Otago and their environment: *Trans. Roy. Soc. New Zealand*, **74,** 71–123.

BERMAN, H. (1937), Constitution and classification of natural silicates: *Am. Mineral.*, **22,** 333–415.

BOWEN, N. L., SCHAIRER, J. F., AND POSNJAK, E. (1933), The system CaO–FeO–SiO_2: *Am. Jour. Sci.*, **26,** 193–284.

BOWEN, N. L., and SCHAIRER, J. F. (1935), The system MgO–FeO–SiO_2: *Am. Jour. Sci.*, **29,** 151–217.

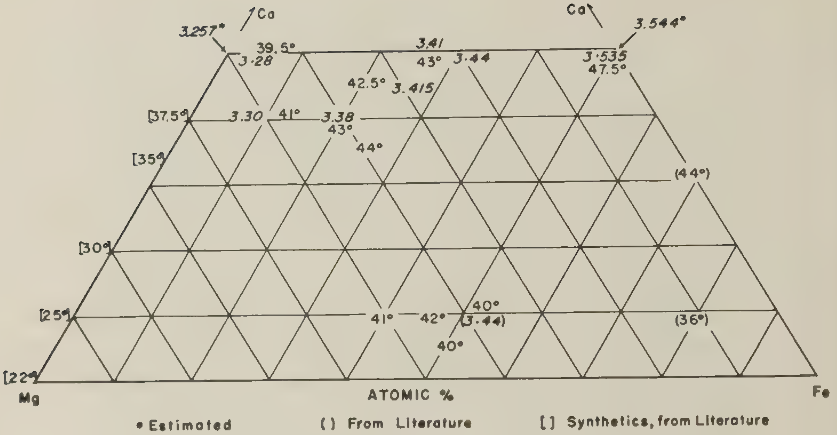


Plate IX. Density variation.

Buddington, A. F. (1939), Adirondack igneous rocks and their metamorphism: *Geol. Soc. Am., Mem.* **7**.

Chapman, R. W., and Williams, C. R. (1935), Evolution of the White Mountain magma series: *Am. Mineral.*, **20**, 512–514.

Dixon, B. E., and Kennedy, W. Q. (1933), Optically uniaxial augite from Aberdeenshire, Scotland: *Zeit. Krist.*, **86**, 112–120.

Foshag, W. F. (1928), The mineralogy and geology of Cerro Mercado, Durango, Mexico: *Proc. U. S. Nat. Mus.*, **74**, art. 23, 1–27.

Hallimond, A. F. (1914), Optical uniaxial augite from Mull: *Mineral. Mag.*, **17**, 97–99.

Hess, H. H. (1941), Pyroxenes of common mafic magmas: *Am. Mineral.*, **26**, 515–535; 573–594.

Larsen, E. S., and Berman, H. (1934), Microscopic determination of the nonopaque minerals. 2nd Ed. *U. S. Geol. Surv., Bull.* **848**, pages 6–7.

Mason, B. (1944), The determination of the density of solids: *Geol. Fören. Förhandl.*, **66**, 27–51.

Niggli, P. (1943), Gesteinschemismus und mineralchemismus II. Die Pyroxene der Magmatischen Erstarrung: *Schweiz. Min. und. Pet. Mitt.*, **23**, 538–607.

Nemoto, T. (1938), A new method of determining extinction angles . . . : *Jour. Fac. Science, Hokkaido Imp. Univ.*, Ser. 4, **4**, 108–122.

Tomita, T. (1934), Variations in optical properties according to chemical composition in the pyroxenes . . . : *Jour. Shanghai Science Instit.*, Sect. II, **1**, 41–58.

Turner, F. J. (1942), Determination of extinction angles in monoclinic pyroxenes and amphiboles: *Am. Jour. Sci.*, **240**, 571–583.

Wager, L. R., and Deer, W. A. (1939), Geological investigations East Greenland; petrology of the Skaergaard intrusion: *Medd om Grønland*, **105**, 335 pp.

Warren, B. E., and Lawrence, W. (1928), The structure of diopside Ca Mg $(SiO_3)_2$: *Zeit. Krist.*, **69**, 168.

Winchell, A. N. (1923), Studies in the pyroxene group: *Am. Jour. Sci.*, **4**, 503–520.

——— (1935), Further studies in the pyroxene group: *Am. Mineral.*, **20**, 562–568.

Wright, F. E. (1911), Methods of petrographic-microscopic research: *Carnegie Institute of Washington, Publication* **158**.

TABLES OF ANALYSES

abbreviations

R.A.L. = Rock Analysis Laboratory. University of Minnesota.
A.F.B. = A. F. Buddington (1939).

ANALYSIS 1

Specimen No. WEB. Chrome Diopside. Webster, North Carolina, from Websterite

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	54.38	Si	905½								Z	
Al_2O_3	1.29						1	24			930½	2.02
Fe_2O_3	2.19	Al	25	– –	–	– –	–	– –	–	– –		
FeO	.94											
MgO	16.96	Fe'''	27½	3				24½				
CaO	23.71	Cr	3½			3½						
Na_2O	.14	Fe	13									
K_2O	.08	Mn	1½									
H_2O+	.14	Ni	—									
H_2O-	.08	Mg	420½								WXY	1.95
TiO_2	.04	Ca	423								893	
Cr_2O_3	.28	Na	4½	1		3½						
MnO	.09	K	2	2								
NiO	.00	Ti	½				½					
P_2O_5	.10	O	2757									
	100.42											

Analyst: A. H. Phillips
Density: 22°/4° 3.32(?)
Color hand specimen: Emerald green

$Ca_{47.8}Mg_{47.5}Fe_{4.7}$
% Al in Z = 2.7

Indices of Refraction

nX	1.6715
nY	1.6782
nZ	1.7007

Pleochroism

Colorless in section

Birefringence, x10^4 aver. 292
287, 290, 293, 297, 298

2V aver. 57¾°
57°, 57½°, 58¼°, 58¼°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B none}\\ \text{A weak}\end{matrix}\right\} r > v$

Z∧*c* aver. 39°

Exsolution Lamellae, rare ∥{001}

Remarks:
Chemical analysis good but not of superior quality.

ANALYSIS 2

Specimen No. 7666. Chrome Diopside. From bronzitite, Malips Drift Camp, Bushveld Complex. Analyzed mineral only present in minute amounts in this rock. Collected by E. Sampson

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	54.07	Si	900								Z	
Al_2O_3	2.08						6	8	2	12	928	2.01
Fe_2O_3	.56	Al	40	– –	–	– –	–	– –	–	– –		
FeO	2.53									12		
MgO	17.39	Fe'''	8					8				
CaO	22.12	Cr	14			12			2			
Na_2O	.41	Fe	35									
K_2O	.00	Mn	1									
H_2O+	.04	Ni	1								WXY	1.98
H_2O-	.06	Mg	431								911	
TiO_2	.21	Ca	394									
Cr_2O_3	.98	Na	12			12						
MnO	.09	K	—									
NiO	.04	Ti	3				3					
		O	2767									
	100.58											

Analyst: R. B. Ellestad
Color hand specimen: Emerald green

$Ca_{45}Mg_{50}Fe_5$
% Al in Z = 3.0

Indices of Refraction

nX	1.6742
nY	1.6800
nZ	1.7019

Pleochroism

Colorless in section

Birefrigence, x10^4 aver. 277
254, 272, 272, 276, 278, 280, 288, 291
highly variable

2V aver. 55½°
54¾, 55, 55½, 56½°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A weak}\end{matrix}\right\} r > v$

Z∧*c* aver. 40¼°
39½, 39¾, 40, 40, 40½, 41°

Exsolution Lamellae, rare, if any.

Remarks:

ANALYSIS 3

Specimen No. PG 50. Chrome augite. Cayoguan chromite deposit, Moa district, Oriente, Cuba. Rock a medium coarse feldspathic peridotite which grades into gabbro pegmatite cutting chromite ore.

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	51.98	Si	865½								Z	
Al_2O_3	3.67						4	8	9	25	911½	1.99
Fe_2O_3	.62	Al	72									
FeO	3.62									26		
MgO	18.28	Fe'''	8					8				
CaO	20.13	Cr	16			7			9			
Na_2O	.17	Fe	50									
K_2O	.08	Mn	2									
H_2O+	.11	Ni	—								WXY	2.02
H_2O-	.03	Mg	453								923	
TiO_2	.15	Ca	359									
Cr_2O_3	1.21	Na	5			5						
MnO	.14	K	2			2						
NiO	.03	Ti	2				2					
		O	2747									
	100.2_2											

Analyst: Lee C. Peck
Color hand specimen: light green

$Ca_{41}Mg_{52}Fe_7$
% Al in Z=5.0

Indices of Refraction
*n*X 1.6797
*n*Y 1.6844
*n*Z 1.7058

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 261
255, 258, 261, 263, 269

2V aver. 50°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A weak}\end{matrix}\right\} r>v$

Z∧*c* aver. 40¾°

Exsolution Lamellae, ‖{100}

Remarks:

ANALYSIS 4

Specimen No. MVL 101/2. Chrome augite. From pegmatitic olivine plagioclase rock below chromite horizon, Mountain View Lake, west side. Stillwater Valley. Stillwater Complex, Montana.

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	51.43	Si	856								Z	
Al_2O_3	3.00						7	17	5	15	900	1.99
Fe_2O_3	1.37	Al	58									
FeO	4.23									15		
MgO	19.44	Fe'''	17					17				
CaO	17.86	Cr	14			9			5			
Na_2O	.28	Fe	59									
K_2O	.02	Mn	2									
H_2O+	.70	Ni	—								WXY	2.00
H_2O-	.10	Mg	482								905	
TiO_2	.27	Ca	319									
Cr_2O_3	1.09	Na	9			9						
MnO	.14	K	—									
NiO	—	Ti	3½				3½					
		O	2719									
	99.93											

Analyst: R. B. Ellestad
Color hand specimen: Emerald green

$Ca_{37}Mg_{56}Fe_7$
% A in Z=4.9

Indices of Refraction
*n*X 1.6810
*n*Y 1.6853
*n*Z 1.7057

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 247
230, 238, 238, 242, 248, 248,250, 252, 259
268, (280?).

2V aver. 48¾°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\ \text{A moderate}\end{matrix}\right\} r>v$

Z∧*c* aver. 40½°
39½, 39¾, 40¾, 41, 41°

Exsolution Lamellae, ‖{100}

Remarks:

ANALYSIS 5

Specimen No. I 52. Chrome augite. From pegmatitic gabbro below chromite horizon. Stillwater Complex. Montana.

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	52.55	Si	875								Z	
Al_2O_3	2.98						6	14	6	16	917	2.00
Fe_2O_3	1.17	Al	58									
FeO	3.98									16		
MgO	18.21	Fe'''	14					14				
CaO	19.23	Cr	16			10			6			
Na_2O	.32	Fe	55									
K_2O	.00	Mn	2									
H_2O+	.14	Ni	1								WXY	
H_2O-	.08	Mg	451½								912½	2.00
TiO_2	.24	Ca	344									
Cr_2O_3	1.18	Na	10			10						
MnO	.12	K	—									
NiO	.05	Ti	3				3					
		O	2746½									
	100.25											

Analyst: R. B. Ellestad
Density: 20°/4° 3.299
Color hand specimen: Emerald green

$Ca_{40}Mg_{52}Fe_8$
% Al in Z=4.6

Indices of Refraction
*n*X 1.6805
*n*Y 1.6852
nZ 1.7075

Pleochroism

Colorless in section

Birefringence, x10^4 aver. 270
249, 254, 258, 272, 272, 276, 282, 295 (variable).

2V aver. 49°
49, 49, 49¼°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\\text{A moderate}\end{matrix}\right\}r>v$

$Z\wedge c$ aver. 40½°
39, 39¾, 40, 40¼, 40¾, 40¾, 41, 41½, 42¼°

Exsolution Lamellae, ‖{100} well developed

Remarks:

ANALYSIS 6

Specimen No. 7503. Chrome augite. From gabbro above Merensky reef, Rustenburg Platinum Mine, Bushveld Complex. Collected by E. Sampson.

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	52.92	Si	881								Z	
Al_2O_3	2.80						12	5	6	15	919	2.01
Fe_2O_3	.85	Al	54									
FeO	5.57									16		
MgO	16.40	Fe'''	10	5				5				
CaO	19.97	Cr	12			6			6			
Na_2O	.35	Fe	78									
K_2O	.01	Mn	2								WXY	
H_2O+	.10	Ni	1								899	1.97
H_2O-	.07	Mg	407									
TiO_2	.50	Ca	356									
Cr_2O_3	.88	Na	11	5		6						
MnO	.15	K	—									
NiO	.10	Ti	6				6					
		O	2737									
	100.67											

Analyst: R. B. Ellestad
Color hand specimen: green

$Ca_{41.5}Mg_{48}Fe_{10.5}$
% Al in Z=4.2

Indices of Refraction
*n*X 1.6818
*n*Y 1.6865
nZ 1.7085

Pleochroism

Colorless in section

Birefringence, x10^4 aver. 267
253, 262, 267, 273, 274, 274

2V aver. 49°
42¾, 47½, 48, 48¼, 53, 53°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\\text{A weak}\end{matrix}\right\}r>v$

$Z\wedge c$ aver. 40¾°
39¾, 40¾, 41°

Exsolution Lamellae, ‖{100}

Remarks:

ANALYSIS 7

Specimen No. PG 10. Chrome titanaugite. Gabbro pegmatite dike in chromite ore. Moa district, Oriente, Cuba

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	50.90	Si	847								Z	
Al_2O_3	3.83						24	4		23	898	2.00
Fe_2O_3	1.29	Al	74	– –	–	– –	–	– – –	–	– –		
FeO	5.49									23		
MgO	16.07	Fe'''	16	12				4				
CaO	18.92	Cr	11			11						
Na_2O	.69	Fe	76									
K_2O	.06	Mn	3								WXY	
H_2O+	.71	Ni	—								901	2.00
H_2O-	.20	Mg	399									
TiO_2	.94	Ca	338									
Cr_2O_3	.84	Na	22	11		11						
MnO	.19	K	1	1								
NiO (.034)	.03	Ti	12				12					
		O	2697									
	100.16											

Analyst: Lee C. Peck
Color hand specimen: brown

$Ca_{40.7}Mg_{48.3}Fe_{11}$
% Al in Z=5.7

Indices of Refraction
*n*X 1.6825
*n*Y 1.6860
*n*Z 1.7090

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 265
262, 265, 269

2V aver. 48°
45½, 48¾, 52¼°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\ \text{A weak}\end{matrix}\right\} r > v$

Z∧*c* aver. 40¾°

Exsolution Lamellae, ‖{100}

Remarks:

ANALYSIS 8

Specimen No. EB 175. Augite. From feldspathic pyroxenite, East Boulder plateau, Stillwater Complex, Montana

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	52.61	Si	876						Z	
Al_2O_3	2.72					11	8	17	912	2.01
Fe_2O_3	1.36	Al	53	– –	– –	– –	– –	– –		
FeO	5.85							17		
MgO	15.97	Fe'''	17	9			8			
CaO	20.50	Fe	81							
Na_2O	.28	Mn	2½						WXY	
K_2O	.02	Mg	396						894	1.98
H_2O+	.19	Ca	366							
H_2O-	.04	Na	9	9						
TiO_2	.44	K	—							
MnO	.18	Ti	5½			5½				
		O	2718							
	100.16									

Analyst: R. B. Ellestad
Color hand specimen: greenish brown

$Ca_{42.3}Mg_{46}Fe_{11.7}$
% Al in Z=3.9

Indices of Refraction
*n*X 1.6823
*n*Y 1.6874
*n*Z 1.7093

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 270
266, 268, 269, 270, 274, 279

2V aver. 51½°
48¼, 50¾, 51½, 51¾, 52½, 52½, 53°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A very weak}\end{matrix}\right\} r > v$

Z∧*c* aver. 41°
39, 39½, 40, 40¾, 41, 41⅓, 41¼, 41½, 41¾, 41¾, 42¾°

Exsolution Lamellae, ‖{100}. 2V lamellae orthopyroxene = 66° ± 2° = $Mg_{75}Fe_{25}$

Remarks: Twinned on {100}

ANALYSIS 9

Specimen No. 7648. Augite, from norite, Sekukuni, Fighting Kop, Bushveld Complex. Collected by E. Sampson

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	52.47	Si	873½									
Al_2O_3	2.28						12	9		12½	Z 907	2.01
Fe_2O_3	1.49	Al	46	- -	-	- -	-	- -	-	- -		
FeO	6.61									12½		
MgO	15.71	Fe'''	18	9				9				
CaO	20.28	Cr	1		1							
Na_2O	.31	Fe	92									
K_2O	.02	Mn	3								WXY	
H_2O+	.20	Ni	½								894	1.99
H_2O-	.04	Mg	390									
TiO_2	.46	Ca	361									
Cr_2O_3	.08	Na	10	9		1						
MnO	.20	K	—				6					
NiO	.04	Ti	6									
		O	2708									
	100.19											

Analyst: R. B. Ellestad
Color hand specimen: greenish brown

$Ca_{41.5}Mg_{45.5}Fe_{15}$
% Al in Z=3.7

Indices of Refraction
nX 1.6820
nY 1.6875
nZ 1.7101

Pleochroism
Colorless in
in section

Birefringence x10^4 aver. 281
272½, 281, 283, 287½ (margin one grain 254)

2V aver. 51¾°
50¼, 51¾, 52, 52¾°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B moderate}\\ \text{A moderate}\end{matrix}\right\}r>v$

Z∧*c* aver. 42½°

Exsolution Lamellae, a few coarse ‖{001}, fine, numerous ‖{100}

Remarks: Twinned on {100}. Contains a small amount of impurity as follows: hypersthene 0.4%, plagioclase 0.3%, biotite 0.2%.

ANALYSIS 10

Specimen No. EB 43. Augite. From gabbro at base of upper gabbro zone, Stillwater Complex, Montana. East Boulder Plateau area

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	51.83	Si	863							
Al_2O_3	3.07					12	8	20	Z 903	2.007
Fe_2O_3	1.38	Al	60	- -	- -	- -	- -	- -		
FeO	7.21							20		
MgO	16.00	Fe'''	17	9			8			
CaO	19.21	Fe	100							
Na_2O	.27	Mn	2½						WXY	
K_2O	.02	Mg	397						894	1.987
H_2O+	.47	Ca	342½							
H_2O-	.11	Na	9	9						
TiO_2	.49	K	—							
MnO	.17	Ti	6			6				
		O	2700							
	100.23									

Analyst: R. B. Ellestad
Color hand specimen: dark greenish brown

$Ca_{41}Mg_{45}Fe_{14}$
% Al in Z=4.4

Indices of Refraction
nX 1.6832
nY 1.6870
nZ 1.7100

Pleochroism
Colorless in
thin section

Birefringence, x10^4 aver. 268
266, 268, 269

2V aver. 52°. Average of 16 values

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B weak}\\ \text{A none}\end{matrix}\right\}r>v$

Z∧*c* aver. 42.1°. Average of 16 values

Exsolution Lamellae, ‖{100}

Remarks: Twinned on {100}

ANALYSIS 11

Specimen No. EB 41. Augite. From gabbro near uppermost exposure. Stillwater Complex, Montana. East Boulder Plateau area

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	51.86	Si	863									
Al_2C_3	2.33						14	12		9	Z 898	2.02
Fe_2O_3	1.60	Al	44									
FeO	9.45									9		
MgO	14.50	Fe'''	20	8				12				
CaO	18.92	Cr	—									
Na_2O	.23	Fe	131									
K_2O	.00	Mn	3½								WXY 876½	1.97
H_2O+	.37	Ni	—									
H_2O-	.09	Mg	360									
TiO_2	.55	Ca	338									
Cr_2O_3	.01	Na	8	8								
MnO	.24	K	—									
NiO	.02	Ti	7				7					
		O	2674½									
	100.17											

Analyst: R. B. Ellestad
Color hand specimen: dark greenish brown

$Ca_{39.5}Mg_{42.5}Fe_{18}$
% Al in Z=3.9

Indices of Refraction		*Pleochroism*
*n*X	1.6870	Not perceptibly pleochroic in thin section
*n*Y	1.6921	
*n*Z	1.7149	

Birefringence, x10⁴ aver. 279
275, 278, 283

2V aver. 50¾°. Average of 22 values.

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\ \text{A weak}\end{matrix}\right\} r>v$

Z∧*c* aver. 42°. Average of 22 values.

Exsolvtion Lamellae, ‖{001} and ‖{100}

Remarks: Twinned on {100}.

ANALYSIS 12

Specimen No. 7493. Augite. Bushveld Complex, Pretoria district, The Pyramids norite. Collected by E. Sampson

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	51.39	Si	855½							
Al_2O_3	2.45					10	7	15½	Z 888	2.00
Fe_2O_3	1.26	Al	48							
FeO	11.63							15½		
MgO	14.21	Fe'''	16	9			7			
CaO	18.12	Fe	162							
Na_2O	.27	Mn	4½						WXY 888	2.00
K_2O	.02	Mg	352							
H_2O+	.03	Ca	323							
H_2O-	.07	Na	9	9						
TiO_2	.41	K	—							
MnO	.32	Ti	5			5				
		O	2663							
	100.18									

Analyst: R. B. Ellestad
Color hand specimen: brownish green

$Ca_{38.7}Mg_{41}Fe_{21.3}$
% Al in Z=3.7

Indices of Refraction		*Pleochroism*
*n*X	1.6905	Pale smoky green with a purplish tint in most directions but ⊥ *bc* yellowish brown
*n*Y	1.6951	
*n*Z	1.7190	

Birefringence, x10⁴ aver. 285
283, 284, 285, 285, 286

2V aver. 47½°
41, 43¾, 45, 45, 45¼, 46½, 46½, 46¾, 47, 48, 48¼, 48⅜, 48¾, 48⅞, 49¼, 49¾, 50¾, 51, 51½, 53°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B strong}\\ \text{A moderate}\end{matrix}\right\} r>v$

Z∧*c* aver. 44° (average 25 observations)

Exsolution Lamellae, ‖{100} and {001}

Remarks: Twinned on {100}

ANALYSIS 13

Specimen No. 4015. Augite. From mafic gabbro dike in anorthosite, 2 miles S.E. of Gates Corners, Antwerp Quadrangle, Adirondacks. Chemical Analysis of rock A.F.B. no. 47, p. 52

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	51.01	Si	849						Z 884½	2.001
Al_2O_3	2.69					10	8½	17		
Fe_2O_3	1.86	Al	52½	– –	– –	– –	– –	– –		
FeO	10.07							17	WXY 882½	1.997
MgO	12.41	Fe'''	23½	15			8½			
CaC	20.59	Fe	140							
Na_2O	.47	Mn	7							
K_2O	.02	Mg	308							
H_2O+	.19	Ca	367							
H_2O-	.06	Na	15	15						
TiO_2	.40	K	—							
MnO	.48	Ti	5			5				
		O	2651½							
	100.25									

Analyst, L. C. Peck
Density, 3.394 (R. A. L.)
Color hand specimen:

$Ca_{43.5}Mg_{36.5}Fe_{20}$
% Al in Z=4. 2

Indices of Refraction		*Pleochroism*
*n*X	1.6924	X faint green
*n*Y	1.6973	Y pink
*n*Z	1.7193	Z faint green
		‖*c* axis faint green
		⊥ *bc* pink

Birefringence, x10^4 aver. 270
268, 270, 271, 273

2V aver. 50½°
48½, 48½, 49¼, 51½, 52, 52½

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B very weak}\\ \text{A moderate}\end{matrix}\right\} r > v$

Z∧*c* aver. 42½°

Exsolution Lamellae, ‖{100}

Remarks: Rare twinning on {100}

ANALYSIS 14

Specimen No. 5641b. Augite. From metagabbro; garnet-augite-oligoclase-granulite. Dike one mile west of Elizabethville, N. Y. Chemical analysis of rock A.F.B. 64-L, p. 62

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	50.54	Si	841½						Z 873½	2.011
Al_2O_3	2.74					6	4	22		
Fe_2O_3	2.42	Al	54	– –	– –	– –	– –	– –		
FeO	12.80							22	WXY 859½	1.979
MgO	9.65	Fe'''	30	26			4			
CaO	20.16	Fe	178							
Na_2O	.75	Mn	2							
K_2O	.07	Mg	239							
H_2O+	.17	Ca	359½							
H_2O-	.04	Na	24	24						
TiO_2	.25	K	2	2						
MnO	.15	Ti	3			3				
		O	2606½							
	99.74									

Analyst: Lee C. Peck
Density 3.414 (R. A. L.)
Color hand specimen: dark green

$Ca_{41.5}Mg_{29.5}Fe_{26}$
% Al in Z=3.7

Indices of Refraction		*Pleochroism*
*n*X	1.6985	X pale bluish green
*n*Y	1.7055	Y brownish green
*n*Z	1.7270	Z pale bluish green with a trace of pink

Birefringence, x10^4 aver. 280
277, 282, 284. Y−X=215

2V aver. 57½°
55½, 56, 57¾, 58, 59°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B very weak}\\ \text{A moderate}\end{matrix}\right\} r > v$

Z∧*c* aver. 43°?

Exsolution Lamellae, a few ‖{001}

Remarks: Slightly purplish anomalous dispersion.
Small amount of garnet and plagioclase included in above analysis. Possibly 2% impurities.

ANALYSIS 15

Specimen No. 5977. Ferroaugite. Ilmenite-magnetite pyroxenite band in syenite, 1¼ miles west of Kalurah, Oswegatchie quadrangle, Adirondacks. Rock analysis A.F.B. to appear in USGS report on geology of St. Lawrence County magnetite district

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	51.53	Si	858						Z	
Al_2O_3	1.50					5	12½	6	881½	
Fe_2O_3	2.72	Al	29½							
FeO	13.13							6		
MgO	8.92	Fe'''	34	21½			12½			
CaO	20.17	Fe	183							
Na_2O	.67	Mn	12						WXY	
K_2O	.00	Mg	221						859½	1.982
H_2O+	.36	Ca	360							
H_2O-	.06	Na	21½	21½						
TiO_2	.19	K	—							
MnO	.82	Ti	2½			2½				
		O	2602							
	100.07									

Analyst: L. C. Peck
Color hand specimen: medium green

$Ca_{44.5}Mg_{27.25}Fe_{28.25}$
% Al in Z=2.7

Indices of Refraction		*Pleochroism*
nX	1.6995	X, Y and Z pale
nY	1.7063	bluish green,
nZ	1.7280	⊥ *bc* pink

Birefringence, x10^4 aver. 284
278, 278, 285, 288, 290

2V aver. 48½°
47½, 47¾, 48½, 48¾, 49¾, 50¼°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak*}\\ \text{A moderate}\end{matrix}\right\} r>v$

Z∧*c* aver. 42½° variable

Exsolution Lamellae, many ||{100} and {001}
Lamellae are ferrohypersthene $Mg_{22}Fe_{78}$ estimated from 2V=77° negative.

Remarks:
* Peculiar purplish rather than normal bluish dispersion on B optic axis. Margins of crystals have higher birefringence and lower Z∧*c* than cores.

ANALYSIS 16

Specimen No. 1197*a*. Ferrosalite. From marble layer in Whiteface anorthosite, Adirondacks, N. Y. Pokamoonshine Quarry, Ausable Quadrangle

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	50.71	Si	844						Z	
Al_2O_3	1.06					2		9½	855½	2.018
Fe_2O_3	.53	Al	21							
FeO	18.57							9½		
MgO	5.70	Fe'''	6	6						
CaO	22.86	Fe	258½							
Na_2O	.16	Mn	2½						WXY	
K_2O	.02	Mg	141½						832½	1.964
H_2O+	.08	Ca	407½							
H_2O-	.04	Na	6	6						
TiO_2	.07	K	—							
MnO	.18	Ti	1			1				
		O	2543½							
	99.98									

Analyst: Lee C. Peck
Density: 3.413 (R. A. L.)
Color hand specimen: light green

$Ca_{50}Mg_{17}Fe_{33}$
% Al in Z=1.4

Indices of Refraction		*Pleochroism*
nX	1.7080	Faint green not
nY	1.7140	appreciably
nZ	1.7360	pleochroic

Birefringence, x10^4 aver. 280
275, 277, 277, 283, 287
X - Y=69

2V aver. 59¾°
59, 59¼, 59¼, 60¼°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A moderate}\end{matrix}\right\} r>v$

Z∧*c* aver. 43?°

Exsolution Lamellae, none

Remarks:

ANALYSIS 17

Specimen No. 5657*a*. Ferroaugite. Inclusion in granoblastic melanocratic augite syenite; quarry NE of Moody Lake, Saranac Quadrangle, Adirondacks. Chemical analysis of rock A.F.B. #109, p. 120

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	50.33	Si	838						Z	
Al_2O_3	2.32					7	2	18	865	2.022
Fe_2O_3	1.88	Al	45½	– –	– –	– –	– –	– –		
FeO	18.23							18½		
MgO	6.92	Fe'''	23½	21½			2			
CaO	18.39	Fe	254							
Na_2O	.61	Mn	12						WXY	
K_2C	.07	Mg	175½						836½	1.956
H_2O+	.16	Ca	328							
H_2O-	.09	Na	20	20						
TiO_2	.28	K	1½	1½						
MnO	.83	Ti	3½			3½				
		O	2567							
	100.11									

Analyst: Lee C. Peck
Density: 3.397 (R. A. L.)
Color hand specimen: dark green

$Ca_{41.5}Mg_{22}Fe_{36.5}$
% Al in Z=3.2

Indices of Refraction	*Pleochroism*
*n*X 1.7080	X, Y, Z pale bluish green
*n*Y 1.7145	⊥ *bc* plane, pink
*n*Z 1.7350	

Birefringence, x10^4 aver. 270
259, 261, 275, 277; X−Y=65.

2V aver. 57°
56½, 56½, 56¾, 57½, 58½°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B none}\\ \text{A weak}\end{matrix}\right\}r>v$

$Z\wedge c$ aver. 47½°

Exsolution Lamellae, $\parallel\{001\}$ and $\{100\}$

Remarks: Twinned on {100}

ANALYSIS 18

Specimen No. HER. Hedenbergite, Herault, California. Analysis quoted from Wyckoff, Merwin and Washington. *Amer. Journ. Sci.*, 4 ser., **10**, p. 389, 1925. Sample of original material obtained from Merwin. Optical properties determined on this material

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	48.34	Si	805						Z	
Al_2O_3	.30					2	4		811	2.00
Fe_3O_2	1.50	Al	6	– –	– –	– –	– –	– –		
FeO	22.94									
MgC	1.06	*Fe'''	19	5			4			
CaO	21.30	Fe	319							
Na_2O	.14	Mn	53						WXY	
K_2O	.03	Mg	26						803	1.98
H_2O+	.46	Ca	380							
H_2O-	—	Na	5	5						
TiO_2	.08	K	—							
MnO	3.70	Ti	1							
		O	2430							
	99.85									

Analyst: E. S. Shepherd
Density: 22°/4° 3.535
Color hand specimen: dark brown

$Ca_{47.7}Mg_{3.2}Fe_{49.1}$
% Al in Z=0.8

Indices of Refraction	*Pleochroism*
*n*X 1.7225	Colorless in section
*n*Y 1.7300	or faint brown
*n*Z 1.7505	nonpleochroic

Birefringence x10^4 aver. 280
268, 270, 272, 273, 274, 280, 295, 287, 289, 300

2V aver. 62½°
Range 61°–67°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B none}\\ \text{A strong}\end{matrix}\right\}r>v$

$Z\wedge c$ aver. 47½°
Range 46°–49°

Exsolution Lamellae, rare $\parallel\{001\}$

Remarks: Pair and multiple twins with {100} composition plane. Good {100} and {010} partings.

* Insufficient Al^{+3} to balance electrical charge Fe^{+3} by substitution Al^{+3} for Si^{+4}

ANALYSIS 19

Specimen No. 4785. Ferroaugite. From quartz syenite, quarry ⅞ mile NE Ausable Forks, N. Y. Chemical analysis of rock A.F.B. #113, p. 120

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	48.28	Si	804						Z 820½	2.02
Al_2O_3	1.45					7		9½		
Fe_2O_3	3.96	Al	28							
FeO	27.02				2			9½	WXY 800	1.97
MgO	.32	Fe'''	50	50						
CaO	16.18	Fe	376							
Na_2O	1.51	Mn	10½							
K_2O	.14	Mg	8							
H_2O+	.15	Ca	188½							
H_2O-	.15	Na	49	47	2					
TiO_2	.28	K	3	3						
MnO	.76	Ti	3½			3½				
		O	2441							
	100.20									

Analyst: L. C. Peck
Color hand specimen: medium green

$Ca_{39.5}Mg_1Fe_{59.5}$
% Al in Z=2. 0

Indices of Refraction
*n*X 1.7355
*n*Y 1.7450
*n*Z 1.7650

Pleochroism
X blue green
Y yellow green
Z yellow green
c axis blue green
⊥ *bc* brownish yellow green

Birefringence, x10^4 aver. 295
283, 295, 297, 297, 299

2V aver. 70¼°

Dispersion, Opt. Ax. {B strong *v*} >*r*
{A strong *r*} >*v*

Z∧*c* aver. 56½(?)°

Exsolution Lamellae, ∥{001} coarse

Remarks:

ANALYSIS 20

Specimen No. TrM 2. Augite. From contaminated granite gneiss, Lyon Mt. Quadrangle, N. Y. Collected by and published by permission of A. W. Postel

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	52.11	Si	867½						Z 889½	2.01
Al_2O_3	1.86					2	5½	14½		
Fe_2O_3	4.59	Al	36½							
FeO	7.93							14½	WXY 879½	1.99
MgO	11.32	Fe'''	57½	52			5½			
CaO	20.16	Fe	110½							
Na_2O	1.61	Mn	3							
K_2O	.06	Mg	281							
H_2O+	.12	Ca	360							
H_2O-	.05	Na	52	52						
TiO_2	.06	K	—							
MnO	.23	Ti	1			1				
		O	2650							
	100.10									

Analyst: Lee C. Peck
Color hand specimen: green

$Ca_{44.5}Mg_{31.5}Fe_{21}$
% Al in Z=2.5

Indices of Refraction
*n*X 1.6977
*n*Y 1.7055
*n*Z 1.7240

Pleochroism
X blue green
Y brownish green
Z pale green
⊥ *bc* nearly colorless

Birefringence, x10^4 aver. 263
263, 263, 264

2V aver. 66° variable
61°, 69°, 73°, 75± °

Dispersion, Opt. Ax. {B weak} *r*>*v*
{A moderate} *v*>*r*

Z∧*c* aver. 50° variable

Exsolution Lamellae, probably ∥{100}

Remarks:

ANALYSIS 21

Specimen No. 6072. Augite. From anorthositic gabbro, Keene Valley road, 1 mile WNW intersection with main N-S highway. Elizabethtown quadrangle, N. Y. Chemical analysis rock A.F.B. #25. p. 36

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	49.96	Si	832							
Al_2O_3	4.30					17	7½	29½	Z 886½	2.014
Fe_2O_3	1.96	Al	84	– –	– –	– –	– –	– –		
FeO	8.87							30		
MgO	12.00	Fe'''	24½	17			7½			
CaO	20.43	Fe	123½							
Na_2O	.52	Mn	3							
K_2O	.00	Mg	297½						WXY 878	1.995
H_2O+	.64	Ca	364							
H_2O-	.10	Na	17	17						
TiO_2	.67	K	—							
MnO	.22	Ti	8½			8½				
		O	2640							
	99.67									

Analyst: R. B. Ellestad
Density 25°/4° 3.315 (R. A. L.)
Color hand specimen: medium green

$Ca_{43.75}Mg_{35.75}Fe_{18}$
% Al in Z=6.1

Indices of Refraction
nX 1.6892
nY 1.6950
nZ 1.7164

Pleochroism
Absorption Z>X>Y. All olive green in thick sections. Y slightly yellowish tint and ||c axis slightly bluish tint

Birefringence, x10^4 aver. 272
263, 265, 269, 273, 277, 283

2V aver. 55½°
55, 55½, 55½, 55½

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B weak}\\ \text{A moderate}\end{matrix}\right\}r>v$

Z∧*c* aver. 43(?)°

Exsolution Lamellae, ||{100}

Remarks: Lamellae altered to cloudy opaque material
Not twinned.

ANALYSIS 22

Specimen No. 5915. Augite. From coarse anorthosite, Mt. Marcy, road cut S.W. end of outlet Lake Clear, St. Regis quadrangle. Chemical analysis of rock A.F.B. #7, p. 24

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	50.13	Si	834½							
Al_2O_3	4.71					14		32½	Z 881	2.018
Fe_2O_3	2.67	Al	92	– –	– –	– –	– –	– –		
FeO	9.66				13			32½		
MgO	10.98	Fe'''	17	17						
CaO	19.54	Fe	134½							
Na_2O	.81	Mn	3							
K_2O	.14	Mg	272						WXY 857½	1.964
H_2O+	.91	Ca	348½							
H_2O-	.05	Na	27	14	13					
TiO_2	.58	K	3	3						
MnO	.23	Ti	7			7				
		O	2619½							
	100.41									

Analyst: R. B. Ellestad & L. C. Peck
Density: 25°/4° 3.285
Color hand specimen: medium green

$Ca_{45}Mg_{35}Fe_{20}$
% Al in Z=5.3

Indices of Refraction
nX 1.6925
nY 1.6980
nZ 1.7195

Pleochroism
X yellow green
Z blue green

Birefringence, x10^4 aver. 265
238, 242, 257, 260, 260, 266, 267, 272, 280, 287, 291

2V aver. 54½°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B weak}\\ \text{A weak}\end{matrix}\right\}r>v$

Z∧*c* aver. 45¾(?)°

Exsolution Lamellae, coarse ||{100}

Remarks:

ANALYSIS 23

Specimen No. 6102. Salite. Skarn inclusion in gabbroic anorthosite magma. From quarry 2.5 miles SSW of Upper Jay, Lake Placid Quadrangle, N. Y. Chemical analysis of rock A.F.B. #30, p. 36

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	48.81	Si	812						Z	
Al_2O_3	4.37					18	9½	28½	868	2.00
Fe_2O_3	2.12	Al	85½	– –	– –	– –	– –	– –		
FeO	12.70							29		
MgO	8.79	Fe'''	26½	17			9½			
CaO	21.70	Fe	181							
Na_2O	.53	Mn	3						WXY	
K_2O	.00	Mg	218						870½	2.00
H_2O+	.10	Ca	387							
H_2O-	.03	Na	17	17						
TiO_2	.70	K	—							
MnO	.23	Ti	9			9				
		O	2607½							
	100.08									

Analyst: R. B. Ellestad
Density: 24°/4° 3.445 (R. A. L.)
Color hand specimen: black

$Ca_{47.5}Mg_{26.75}Fe_{25.75}$
% Al in Z=6.1

Indices of Refraction		*Pleochroism*
nX	1.6990	X pale gray green
nY	1.7048	Y pale brownish green
nZ	1.7260	Z pale gray green
		⊥ *bc* pink

Birefringence, x10^4 aver. 270
268, 269, 270, 274

2V aver. 56°
55½, 55½, 55¾, 56½, 56½, margins 1° higher than cores

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B strong}\\ \text{A moderate}\end{matrix}\right\} r > v$

$Z \wedge c$ aver. 45?°

Exsolution Lamellae, none

Remarks: not twinned.

ANALYSIS 24

Specimen No. 6053. Salite. From granoblastic Whiteface gabbroic anorthosite. Quarry 0.3 miles east of Stickney Bridge, Ausable Quadrangle. Chemical analysis of rock A.F.B. #10, p. 24

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	45.80	Si	762½						Z	
Al_2O_3	7.06					36	17	42½	858	1.997
Fe_2O_3	3.14	Al	138½	– –	– –	– –	– –	– –		
FeO	10.29							43		
MgO	8.42	Fe'''	39	22			17			
CaO	21.58	Fe	143							
Na_2O	.68	Mn	3						WXY	
K_2O	.01	Mg	209						862	2.006
H_2O+	.30	Ca	385							
H_2O-	.10	Na	22	22						
TiO_2	1.42	K	—							
MnO	.20	Ti	18			18				
		O	2578							
	99.00*									

Analyst: R. B. Ellestad
Density: 25°/4° 3.389 (R. A. L.)
Color hand specimen: black

$Ca_{49.5}Mg_{26.75}Fe_{23.75}$
% Al in Z=11.2

Indices of Refraction		*Pleochroism*
nX	1.7087	Z=X olive green
nY	1.7140	Y brownish green
nZ	1.7339	⊥ *bc* pink
		Colors very faint in thin section

Birefringence, x10^4 aver. 247
245, 245, 248, 251

2V aver. 56°
55, 55¼, 55¼, 56, 56¼, 57°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B strong}\\ \text{A weak}\end{matrix}\right\} r > v$

$Z \wedge c$ aver. 44(?)°

Exsolution Lamellae, none

Remarks: not twinned.

* Low summation, probably some carbonate alteration decreasing SiO_2. CO_2 not determined.

ANALYSIS 25

Specimen No. 6020A. Ferrosalite. From skarn inclusion in gabbroic anorthosite, 1.9 miles SW of Willsboro bridge, Willsboro Quadrangle, N. Y. Chemical analysis of rock A.F.B. #38, p. 44

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	45.30	Si	754						Z	
Al_2O_3	7.74					32	10	55	851	1.98
Fe_2O_3	3.36	Al	152	– –	– –	– –	– –	– –		
FeO	12.27							55		
MgO	7.04	Fe'''	42	32			10			
CaO	21.74	Fe	171							
Na_2O	.88	Mn	2						WXY	
K_2O	.16	Mg	175						876	2.04
H_2O+	.39	Ca	383							
H_2O-	.06	Na	28	28						
TiO_2	1.30	K	4	4						
MnO	.15	Ti	16			16				
		O	2578							
	100.39									

Analyst: R. B. Ellestad & L. C. Peck
Density: 27°/4° 3.449 (R. A. L.)
Color hand specimen: black

$Ca_{49.5}Mg_{22.5}Fe_{28}$
% Al in Z=11.4

Indices of Refraction		*Pleochroism*
nX	1.7154	X purplish green
nY	1.7208	Y pinkish purple
nZ	1.7402	Z yellowish green
		‖c axis bluish green
		⊥ *bc* pinkish brown

Birefringence, x10^4 aver. 245
237, 239, 247, 247, 250, 252

2V aver. $57\frac{1}{4}$°
$56\frac{3}{4}$, $57\frac{1}{4}$, $57\frac{1}{4}$, $57\frac{3}{4}$°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B strong}\\ \text{A weak}\end{matrix}\right\} r>v$

Z∧*c* aver. $46\frac{1}{2}$(?)°

Exsolution Lamellae, fine ‖{100} a few |{001}

Remarks:
Some sphene inclusions, probably exsolution products.

ANALYSIS 26

Specimen No. 6101*a*. Ferrosalite. From gabbro pegmatite in Mt. Marcy anorthosite. Quarry 3 miles east of Wilmington on south shoulder of Hamlin Mt., Lake Placid Quadrangle, N. Y. Chemical analysis of rock A.F.B. #26, p. 36

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	46.85	Si	780						Z	
Al_2O_3	5.03					37	$21\frac{1}{2}$	20	$858\frac{1}{2}$	2.007
Fe_2O_3	2.91	Al	$98\frac{1}{2}$	– –	– –	– –	– –	– –		
FeO	13.63							20		
MgO	7.03	Fe'''	$36\frac{1}{2}$	15			$21\frac{1}{2}$			
CaO	21.90	Fe	190							
Na_2O	.46	Mn	3						WXY	
K_2O	.00	Mg	$174\frac{1}{2}$						848	1.982
H_2O+	.24	Ca	$390\frac{1}{2}$							
H_2O-	.05	Na	15	15						
TiO_2	1.47	K	—							
MnO	.20	Ti	$18\frac{1}{2}$			$18\frac{1}{2}$				
		O	2567							
	99.77									

Analyst: R. B. Ellestad
Density: 23°/4° 3.449
Color hand specimen: black

$Ca_{49}Mg_{22}Fe_{29}$
% Al in Z=9.1

Indices of Refraction		*Pleochroism*
nX	1.7095	X pale bluish green
nY	1.7153	Y pale green with pink tint
nZ	1.7350	Z pale yellowish green
		⊥ *bc* pink
		Weakly colored in thin section

Birefringence, x10^4 aver. 255
250, 256, 257

2V aver. $54\frac{1}{4}$°
$53\frac{3}{4}$, $54\frac{1}{4}$, $54\frac{1}{4}$, $54\frac{1}{4}$

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B strong}\\ \text{A moderate}\end{matrix}\right\} r>v$

Z∧*c* aver. 44(?)°

Exsolution Lamellae, none

Remarks: Much exsolved sphene as minute blebs or rods (checked by *x*-ray).
Not twinned
Host material minus sphene
$=Ca_{48}Mg_{22.5}Fe_{29.5}$. 7.3% Al in Z.

ANALYSIS 27

Specimen No. Percy (19258, Harvard No.). Ferroaugite. From syenite, White Mountain magma series, Percy Quadrangle, New Hamp. Quoted from Chapman and Williams. *Amer. Min.* 20, p. 512, 1935. Optical properties redetermined

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	47.58	Si	797						Z	
Al_2O_3	1.16					9	13½		819½	2.002
Fe_2O_3	2.60	Al	22½	– –	– –	– –	– –	– –		
FeO	24.21									
MgO	3.34	Fe'''	32½	19			13½			
CaO	18.80	Fe	337							
Na_2O	.47	Mn	8½						WXY	
K_2O	.21	Mg	83						819½	2.002
H_2O+	.34	Ca	335							
H_2O-		Na	15	15						
TiO_2	.37	K	4	4						
MnO	.59	Ti	4½			4½				
		O	2456½							
	99.67									

Analyst: F. A. Gonyer
Color hand specimen: medium green

$Ca_{42}Mg_{10.5}Fe_{47.5}$
% Al in Z=2.7

Indices of Refraction
*n*X 1.7258
*n*Y 1.7327
*n*Z 1.7550

Pleochroism
X, Y, Z yellow green
⊥ *bc* yellow
Weakly pleochroic

Birefringence, x10^4 aver. 292
286, 287, 290, 291, 294, 295

2V aver. 58½°
56¾, 58¼, 59¼, 59½°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B moderate}\\\text{A strong}\end{matrix}\right\}\begin{matrix}v>r\\r>v\end{matrix}$

Z∧*c* aver. 48(?)°

Exsolution Lamellae, none

Remarks:

ANALYSIS 28

Specimen No. 9639. Titanaugite. Duluth gabbro, collected by E. Sampson. From fine grained biotite gabbro in city of Duluth. 150 yds. NE of top of inclined railway at small quarry

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	50.79	Si	845								Z	
Al_2O_3	3.48						26	5	3	17	896	2.00
Fe_2O_3	1.37	Al	68	– –	–	– –	–	– –	–	– –		
FeO	9.41									17		
MgO	14.64	Fe'''	17	12				5				
CaO	18.55	Cr	3						3			
Na_2O	.36	Fe	131									
K_2O	.03	Mn	3½								WXY	
H_2O+	.03	Ni	—								890½	1.99
H_2O-	.04	Mg	363									
TiO_2	1.03	Ca	331									
Cr_2O_3	.25	Na	12	12								
MnO	.24	K	—									
NiO	.03	Ti	13				13					
		O	2682½									
	100.25											

Analyst: R. B. Ellestad
Color hand specimen: dark brown

$Ca_{39}Mg_{43}Fe_{18}$
% Al in Z=5.7

Indices of Refraction
*n*X 1.6930
*n*Y 1.6968
*n*Z 1.7215

Pleochroism
Pale purplish brown not appreciably pleochroic

Birefringence, x10^4 aver. 285
282, 285½, 287

2V aver. 43½°
42½, 42½, 43½, 44¾, 45°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B strong}\\\text{A weak}\end{matrix}\right\}r>v$

Z∧*c* aver. 43½°

Exsolution Lamellae, none

Remarks:

ANALYSIS 29

Specimen No. D3. Titanaugite. Coarse diabase pegmatite. Bluff east of Dutchmans Lake. Sec. 7, T 63 N, R 6 E. Cook Co., Minn. Supplied by F. F. Grout

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	50.76	Si	845								Z	
Al_2O_3	2.83						25	8		11½	889½	2.00
Fe_2O_3	1.35	Al	56	– –	–	– –	–	– –	–	– –		
FeO	10.23									11½		
MgO	14.22	Fe'''	16	8				8				
CaO	19.08	Cr	2			2						
Na_2O	.32	Fe	142									
K_2O	.00	Mn	3½								WXY	
H_2O+	.02	Ni	—								889½	2.00
H_2O-	.01	Mg	352½									
TiO_2	.99	Ca	—									
Cr_2O_3	.19	Na	—	8		2						
MnO	.25	K	—									
NiO	.02	Ti	—				12½					
		O	2669									
	100.27											

Analyst: R. B. Ellestad

Color hand specimen: dark brown, almost black

$Ca_{39.7}Mg_{41.4}Fe_{18.9}$

% Al in Z=5

Indices of Refraction

		Pleochroism
*n*X	1.6941	Faint purplish brown not perceptibly pleochroic in thin sections.
*n*Y	1.6984	
*n*Z	1.7218	

Birefringence, x10^4 aver. 277
272, 275½, 277, 281, 282

2V aver. 46¾°
46¼, 47¼°

Dispersion, Opt. Ax.$\left\{\begin{array}{l}\text{B moderate}\\ \text{A weak}\end{array}\right\}r>v$

Z∧*c* aver. 44°

Exsolution Lamellae, none

Remarks:

ANALYSIS 30

Specimen No. D2. Titanaugite. From pegmatitic zone in gabbro sill, shore of Lake Superior; Sec. 35, T 63 N, R 5 E. Cook Co., Minn. Supplied by F. F. Grout

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	50.85	Si	846									
Al_2O_3	2.70						26	6		10	888	2.00
Fe_2O_3	1.11	Al	52	– –	–	– –	–	– –	–	– –		
FeO	10.36									10		
MgO	14.09	Fe'''	14	8				6				
CaO	19.20	Cr	2			2						
Na_2O	.30	Fe	144									
K_2O	.00	Mn	3½								WXY	
H_2O+	.01	Ni	—								888½	2.00
H_2C-	.09	Mg	349									
TiO_2	1.05	Ca	343									
Cr_2O_3	.13	Na	10	8		2						
MnO	.25	K	—									
NiO	.02	Ti	13				13					
		O	2666½									
	100.16											

Analyst: R. B. Ellestad
Density: 24°/4° 3.383
Color hand specimen: dark brown almost black

$Ca_{40}Mg_{41.1}Fe_{18.9}$

% Al in Z=4.7

Indices of Refraction

		Pleochroism
*n*X	1.6937	Z, X faint purplish brown color
*n*Y	1.6982	Y pink
*n*Z	1.7221	

Birefringence, x10^4 aver. 284
279, 283½, 284, 285, 287½

Z−Y=239, 241, 241

2V aver. 47°
46¼, 46½, 46½, 47, 47½, 48¼°

Dispersion, Opt. Ax.$\left\{\begin{array}{l}\text{B moderate}\\ \text{A weak}\end{array}\right\}r>v$

Z∧*c* aver. 44°

Exsolution Lamellae, none

Remarks:

ANALYSIS 31

Specimen No. W. Titanaugite, gabbro sill vicinity of Pigeon Point, Minn. (?)
Supplied by A. N. Winchell

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Cr	Ti	Fe'''	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	50.85	Si	846½								Z	
Al_2O_3	2.38						26	3		9½	885	2.00
Fe_2O_3	.96	Al	48									
FeO	11.92									9½		
MgO	13.50	Fe'''	12	9				3				
CaO	18.80	Cr	—									
Na_2O	.28	Fe	165									
K_2O	.00	Mn	4								WXY	
H_2O+	.04	Ni	—								883½	2.00
H_2O-	.04	Mg	335									
TiO_2	1.03	Ca	336									
Cr_2O_3	.03	Na	9	9								
MnO	.29	K	—									
NiO	.01	Ti	13				13					
P_2O_5	.00	O	2653½									
	100.13											

Analyst: R. B. Ellestad
Color hand specimen: dark brown or black

$Ca_{39.5}Mg_{39.5}Fe_{21}$
% Al in Z=4.3

Indices of Refraction
nX 1.6954
nY 1.7005
nZ 1.7250

Pleochroism
Faint pleochroism in pale purplish brown X=Y=Z, ⊥ *bc* lighter colored yellowish brown

Birefringence, x10^4 aver. 296
289, 293, 297, 297½, 300, 300

2V aver. 49°
44, 47, 47½, 48¼, 48½, 48½, 51½, 53, 53¼°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\ \text{A none}\end{matrix}\right\} r>v$

$Z \wedge c$ aver. 44(?)°

Exsolution Lamellae, rare ∥{001}

Remarks:

ANALYSIS 32*

Specimen No. LAM 12A. Augite. From diabase sill in Triassic, south of Lambertville, N. J. From wall of quarry 750 feet above base of sill approximately and 1000 feet below, roof

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	50.74	Si	845						Z	
Al_2O_3	3.21					12		25	882	2.001
Fe_2O_3	.70	Al	63							
FeO	13.07				1			25		
MgO	13.45	Fe'''	9	9						
CaO	17.40	Fe	182							
Na_2O	.30	Mn	4½						WXY	
K_2O	.06	Mg	333½						881	1.999
H_2O+	.28	Ca	310							
H_2O-	.01	Na	9	8	1					
TiO_2	.46	K	1	1						
MnO	.32	Ti	6			6				
		O	2645							
	100.00*									

Analyst: Lee C. Peck

Color hand specimen: brown with slight purple tint

$Ca_{37}Mg_{39.7}Fe_{23.8}$
% Al in Z=4.2

Indices o Refraction
nX 1.6950
nY 1.6990 Range
nZ 1.7220 ±.002

Pleochroism
Barely pleochroic X=Y=Z purplish brown
⊥ *bc* light brown

Birefringence, x10^4 aver. 270
267, 270, 271, 273

2V aver. 43½°
41⅛, 42½, 43, 43½, 43½, 43½, 44¼, 45¾°
Rims about 6° higher than cores

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\ \text{A weak}\end{matrix}\right\} r>v$

$Z \wedge c$ aver. 43½(?)°

Exsolution Lamellae, numerous ∥{001}

Remarks: Twinned on {100}.

* Impurity 6% pigeonite LAM 12 P. Pigeonite also analyzed and appropriate correction has been applied to above analysis by subtracting pigeonite and calculating to 100%.

ANALYSIS 33

Specimen No. TR-1-A. Augite. Coarse diabase pegmatite. Goose Creek, Va.
(Triassic) Pigeonite TR-1-P also analyzed

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	50.53	Si	841							
Al_2O_3	2.49					22		13½	Z 876½	1.999
Fe_2O_3	.59	Al	49							
FeO	14.25				½			13½		
MgO	13.08	Fe'''	7½	7½						
CaO	17.38	Fe	198							
Na_2O	.23	Mn	5½						WXY	
K_2O	.03	Mg	324½						878	2.002
H_2O+	.25	Ca	310							
H_2O-	.09	Na	8	7½	½					
TiO_2	.87	K	—							
MnO	.38	Ti	11			11				
		O	2631							
	100.17									

Analyst: Lee C. Peck
Color hand specimen: brown with slight purplish tint

$Ca_{36.7}Mg_{38.4}Fe_{24.9}$
% Al in Z=4.1

Indices of Refraction
nX 1.6972
nY 1.7005
nZ 1.7240

Pleochroism
Light purplish brown
Pleochroism not evident in thin section

Birefringence, x10^4 aver. 285

2V aver. 40°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B moderate}\\ \text{A weak}\end{matrix}\right\}r>v$

$Z \wedge c$ aver. 44°

Exsolution Lamellae, none

Remarks: Twinned on {100}

ANALYSIS 34*

Specimen No. Dil 3. Augite. Diabase dike, Dillsburg Quadrangle, Pa.
(Triassic). Collected by P. Hotz

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	50.72	Si	843							
Al_2O_3	2.28					21	1½	10	Z 875½	2.01
Fe_2O_3	.84	Al	44							
FeO	16.32							10½		
MgO	12.63	Fe'''	10½	9			1½			
CaO	15.46	Fe	227							
Na_2O	.28	Mn	4½						WXY	
K_2O	.00	Mg	313						860½	1.98
H_2O+	.22	Ca	275½							
H_2O-	.08	Na	9	9						
TiO_2	.84	K	—							
MnO	.33	Ti	10½			10½				
		O	2613							
	100.00*									

Analyst: Lee C. Peck
Color hand specimen: brown

$Ca_{33}Mg_{38}Fe_{29}$
% Al in Z=3.7

Indices of Refraction
nX 1.6950
nY 1.7010
nZ 1.7240

Pleochroism
Faint purplish brown not appreciably pleochroic

Birefringence, x10^4 aver. 265
258, 261, 261, 263, 264, 265, 268, 269, 270, 271

2V aver. 44°

Dispersion, Opt. Ax.$\left\{\begin{matrix}\text{B weak}\\ \text{A none}\end{matrix}\right\}r>v$

$Z \wedge c$ aver. 43½°

Exsolution Lamellae, none

Remarks: Twinned on {100}

* Estimated impurity 10% pigeonite. Analysis corrected by subtraction of 10% pigeonite of appropriate composition and recalculated to 100%.

ANALYSIS 35

Specimen No. BH 1.23. Diopside. Skarn rock, Brunner Hill magnetite deposit near Colton, Stork Quadrangle, St. Lawrence Co. N. Y.; 2.8 miles WNW of Catamount Mt. Collected by B. F. Leonard

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	54.51	Si	908½						Z	
Al_2O_3	.40					1	2	2½	914	2.00
Fe_2O_3	.40	Al	8							
FeO	2.35							2½		
MgO	17.19	Fe'''	5	3			2			
CaO	24.90	Fe	33							
Na_2O	.06	Mn	2½						WXY	
K_2O	.05	Mg	426						916½	2.00
H_2O+	.03	Ca	444							
H_2O-	.03	Na	2	2						
TiO_2	.04	K	1	1						
MnO	.16	Ti	½			½				
		O	2744½							
	100.12									

Analyst: Lee C. Peck
Density: 19°/4° 3.281
Color hand specimen: Very pale green

$Ca_{48.8}Mg_{46.8}Fe_{4.4}$
% Al in Z=0.6

Indices of Refraction
*n*X 1.6718
*n*Y 1.6785
*n*Z 1.7013

Pleochroism
Colorless

Birefringence, x10^4 aver. 295
289, 295, 299

2V aver. 56½°
54½, 56¾, 56¾, 57¼, 57¾°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A weak}\end{matrix}\right\} r>v$

Z∧*c* aver. 39½°

Exsolution Lamellae, none

Remarks:

ANALYSIS 36

Specimen No. CN 20.4. Diopside. Skarn rock from Clifton Mine, magnetite deposit, Stark Quadrangle, St. Lawrence Co., N. Y. 3.5 miles SE Degrasse hamlet. Collected by B. F. Leonard

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	53.79	Si	896						Z	
Al_2O_3	1.41					1		13	910	1.996
Fe_2O_3	.33	Al	28							
FeO	2.60				1			13		
MgO	16.64	Fe'''	4	4						
CaO	24.66	Fe	36							
Na_2O	.14	Mn	3						WXY	
K_2O	.04	Mg	413						915½	2.008
H_2O+	.10	Ca	440							
H_2O-	.04	Na	4½	4	½					
TiO_2	.04	K	½		½					
MnO	.22	Ti	½			½				
Cr_2O_3	.00	O	2735½							
NiO	.00									
	100.01									

Analyst: Lee C. Peck
Color hand specimen: white

$Ca_{49}Mg_{46}Fe_5$
% Al in Z=1.5

Indices of Refraction
*n*X 1.6740
*n*Y 1.6805
*n*Z 1.7029

Pleochroism
Colorless

Birefringence, x10^4 aver. 289
286½, 288, 288, 290, 292

2V aver. 56¾°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A weak}\end{matrix}\right\} r>v$

Z∧*c* aver. 39½°

Exsolution Lamellae, very rare {100}

Remarks: Rare {001} twin lamellae.

Analysis 37

Specimen No. CN 69.1. Salite. Skarn rock. Clifton Mine magnetite deposit collected by B. F. Leonard. Published by permission U. S. Geological Survey.

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	50.19	Si	836						Z 876¾	
Al_2O_3	2.73					6	23½	11¼		1.98
Fe_2O_3	2.98	Al	52	– –	– –	– –	– –	– –		
FeO	7.54							11¼		
MgO	12.38	Fe'''	38	14½			23½			
CaO	23.58	Fe	104							
Na_2O	.45	Mn	6						WXY 903¾	2.04
K_2O	.00	Mg	307							
H_2O+	.00	Ca	420							
H_2O-	.02	Na	14½	14½						
TiO_2	.20	K	—							
MnO	.40	Ti	3			3				
		O	2657							
	100.47									

Analyst: Norman Davidson (U. S. G. S.)
Density 22°/4° 3.373
Color hand specimen: medium green

$Ca_{48}Mg_{35}Fe_{17}$
% Al in Z=4.6

Indices of Refraction
nX 1.6915
nY 1.6980
nZ 1.7185

Pleochroism
X pale bluish green
Y brownish green
Z yellow green
Colorless in thin section

Birefringence, x10^4 aver. 270
269½, 270, 270. Z-Y=210

2V aver. 59°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A weak}\end{matrix}\right\} r>v$

Z∧*c* aver. 45(?)°

Exsolution Lamellae, none

Remarks:

Analysis 38

Specimen No. CN 28.14. Salite. Skarn rock, Clifton mine magnetite deposit. Collected by B. F. Leonard

		Atomic Ratios		Fe''' Na	Al Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O
SiO_2	48.40	Si	805½						Z 864½	
Al_2O_3	3.95					7	33	19		1.993
Fe_2O_3	3.90	Al	78	– –	– –	– –	– –	– –		
FeO	10.52									
MgO	8.92	Fe'''	48	15			33			
CaO	23.20	Fe	146							
Na_2O	.46	Mn	5½						WXY 872	
K_2O	.02	Mg	221							2.010
H_2O+	.16	Ca	414							
H_2O-	.04	Na	15	15						
TiO_2	.27	K	—							
MnO	.39	Ti	3½			3½				
		O	2601							
	100.23									

Analyst: Lee C. Peck
Color hand specimen: dark green

$Ca_{49.5}Mg_{26.5}Fe_{24}$
% Al in Z=6.9

Indices of Refraction
nX 1.7073
nY 1.7140
nZ 1.7328

Pleochroism
X=Y dark blue green
Z yellowish blue green
⊥*bc* yellow brown

Birefringence, x10^4 aver. 255
250, 251, 256, 262½

2V aver. 62°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\ \text{A strong}\end{matrix}\right\} r>v$

Z∧*c* aver. 47½(?)°

Exsolution Lamellae, none

Remarks:

ANALYSIS 39

Specimen No. OF 1.15. Ferrosalite. Skarn rock, Outafit mine, magnetite deposit, Stark Quadrangle, St. Lawrence Co. N. Y. 4 miles NNW of Cranberry Lake village. Collected by B. F. Leonard

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	45.80	Si	763						Z 848½	1.997
Al_2O_3	5.11					8	63	14½		
Fe_2O_3	5.87	Al	100	– –	– –	– –	– –	– –		
FeO	12.44							14½	WXY 856	2.011
MgO	6.86	Fe'''	74	11			63			
CaO	22.54	Fe	173							
Na_2O	.35	Mn	6							
K_2O	.02	Mg	171½							
H_2O+	.17	Ca	402							
H_2O-	.09	Na	11	11						
TiO_2	.31	K	—							
MnO	.41	Ti	4			4				
		O	—							
	99.97									

Analyst: Lee C. Peck
Density: 25°/4° 3.44
Color hand specimen: dark green

$Ca_{48.6}Mg_{20.8}Fe_{30.8}$
% Al in Z=10

Indices of Refraction
nX 1.7210
nY 1.7290
nZ 1.7463

Pleochroism
X dark blue green
Y blue green
Z yellow green
$\perp bc$ brownish yellow

Birefringence, x10^4 aver. 253
249½, 254, 255

2V aver. 67½°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B moderate}\\ \text{A strong}\end{matrix}\right. \begin{matrix} v>r \\ r>v\end{matrix}$

$Z \wedge c$ aver. 51(?)°

Exsolution Lamellae, none

Remarks:

ANALYSIS 40

Specimen No. CM. Augite. Cerro Mercado, Durango, Mexico. U. S. Museum no. 92159. Obtained from E. P. Henderson. U. S. Nat. Mus. Analysis from Foshag (1928)

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	50.97	Si	848						Z 868½	1.97
Al_2O_3	.95					5	15½*			
Fe_2O_3	7.08	Al	18½	– –	– –	– –	– –	– –		
FeO	6.96								WXY 907½	2.06
MgO	11.55	Fe'''	88½	61			15½			
CaO	20.96	Fe	97							
Na_2O	1.86	Mn	—							
K_2O	.05	Mg	286½							
H_2O+	.19	Ca	374							
H_2O-	—	Na	60	60						
TiO_2	.20	K	1	1						
MnO	—	Ti	2½			2½				
		O	2649½							
	100.77									

Analyst: F. A. Gonyer
Color hand specimen: green

$Ca_{44}Mg_{34}Fe_{22}$
% Al in Z=2.3

Indices of Refraction
nX 1.700
nY 1.711
nZ 1.728

Pleochroism
X=Z green, slightly bluish
Y green, slightly yellowish
$\perp bc$ light brown

Birefringence, x10^4 aver. 276
257, 268, 278, 282, 293

2V aver. 77°

Dispersion, Opt. Ax. $\left\{\begin{matrix}\text{B weak}\\ \text{A strong}\end{matrix}\right\} \begin{matrix} r>v \\ v>r\end{matrix}$

$Z \wedge c$ aver. 51°, variable

Exsolution Lamellae

Remarks:
* 2 Fe^{+3} included here in the Z group to balance charge.

Analysis 41*

Specimen No. TR-1-P. Pigeonite. Coarse diabase pegmatite, Goose Creek, Va. (Triassic). See TR-1-A augite analysis from same sample.

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe‴	Al	Ti	Fe‴	Al	Y	
				Na	Na				W	
SiO_2	51.53	Si	858							
Al_2O_3	1.64					13		9	Z 880	2.019
Fe_2O_3	.18	Al	32							
FeO	23.35				1			9		
MgO	17.27	Fe‴	2	2						
CaO	4.47	Fe	325							
Na_2O	.10	Mn	7							
K_2O	.00	Mg	428						WXY 861½	1.976
H_2O+	.32	Ca	80							
H_2O-	.14	Na	3	2	1					
TiO_2	.51	K	—							
MnO	.49	Ti	6½			6½				
		O	2621½							
	100.00*									

Analyst: Lee C. Peck
Color hand specimen: Light brown

$Ca_{9.6}Mg_{50.8}Fe_{39.7}$
% Al in Z=2.5

Indices of Refraction

*n*X	1.6980
*n*Y	1.6988
*n*Z	1.7228

Pleochroism
Colorless

Birefringence, x10^4 aver. 248
Z−X=240

2V aver. 18°⊥{010}
12, 12¼, 16, 19, 19, 20½, 20½, 23°

Dispersion, Opt. Ax. moderate $r>v$†

Z∧*c* aver. 40–41°

Exsolution Lamellae, very fine and regular ∥{001}

Remarks:

* Analysis corrected for augite impurity and recalculated to 100%. Original sample ⅝ pigeonite and ⅜ augite.

† Anomalous dispersion colors greenish blue concave side of isogyre and purple convex side.

Analysis 42*

Specimen No. LAM 12 P. Pigeonite. Diabase sill (Triassic) south of Lambertville, N. J. Sample came from approximately 750 feet above base and 1000 feet below roof.

		Atomic Ratios					2Al	Al	Al	Al	Z	Cations to Six O
				Fe‴	Al	Cr	Ti	Fe‴	Cr	Al	Y	
				Na	Na	Na					W	
SiO_2	51.24	Si	853									
Al_2O_3	1.07						12			4½	Z 869½	2.023
Fe_2O_3	.05	Al	21									
FeO	26.85									4½		
MgO	14.85	Fe‴	1	1								
CaO	4.31	Cr	—									
Na_2O	.02	Fe	374									
K_2O	.02	Mn	8									
H_2O+	.36	Ni	—								WXY 839½	1.986
H_2O-	.18	Mg	368									
TiO_2	.50	Ca	77									
Cr_2O_3	.00	Na	1	1								
MnO	.55	K	—									
NiO	—	Ti	6				6					
		O	2578½									
	100.00*											

Analyst: Lee C. Peck
Color hand specimen: light purplish brown

$Ca_{9.3}Mg_{44.4}Fe_{46.3}$
% Al in Z=1.9

Indices of Refraction

*n*X	1.7055
*n*Y	1.7066
*n*Z	1.7325

Pleochroism
X faint pink
Y faint pink
Z faint green

Birefringence, x10^4 aver. 270
Z−Y=259

2V aver. 22° opt. plane⊥{010}
14, 15¾, 17½, 22½, 23¾, 26, 28, 29°

Dispersion, Opt. Ax. moderate $r>v$

Z∧*c* aver. 42?°

Exsolution Lamellae

Remarks:

* Sample contained 17% augite LAM 12 A also analyzed. Augite subtracted from above analysis and remainder recalculated to 100%.

ANALYSIS 43

Specimen No. MC. Pigeonite. Moore County N.C. meteorite. For description see Hess and Henderson (1949) *Am. Mineral.*, **34**, 499

		Atomic* Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	49.37	Si	822						Z 843	1.996
Al_2O_3	1.55					4	9	8		
Fe_2O_3	1.83	Al	30							
FeO	26.44							9		
MgO	15.54	Fe'''	9				9			
CaO	4.60	Fe	355							
Na_2O	—	Mn	5							
K_2O	—	Mg	385						WXY 847	2.005
H_2O+	—	Ca	82							
H_2O-	—	Na	—							
TiO_2	.62	K	—							
MnO	.37	Ti	2			2				
		O	—							
	100.32									

Analyst: E. P. Henderson
Color hand specimen: light brown

$Ca_{10}Mg_{46}Fe_{44}$†
% Al in Z=2.5

Indices of Refraction
*n*X 1.7085
*n*Y 1.7095
*n*Z 1.7360

Pleochroism
Faint brown
nonpleochroic

Birefringence, x10^4 aver. 275

2V aver. 21°

Dispersion, Opt. Ax. moderate $r>v$

Z∧c aver. 40°

Exsolution Lamellae. Coarse augite lamellae ‖{001}

Remarks:

* $14Fe^{+3}$, $13Fe^{+2}$ and $6Ti^{+4}$ subtracted from these ratios to take care of magnetite-ilmenite inclusions.

† Composition of host less augite lamellae $Ca_5Mg_{47.5}Fe_{47.5}$.

ANALYSIS 44

Specimen No. Mull. Pigeonite. "Uniaxial augite" described by Hallimond (1914) from glassy lava 1 mile south-south-west of Pennygael, Mull. Rock analysis Summ. Prog. of Geol. Surv. Great. Brit. 1912–1913, p. 69

		Atomic Ratios				2Al	Al	Al	Z	Cations to Six O
				Fe'''	Al	Ti	Fe'''	Al	Y	
				Na	Na				W	
SiO_2	49.72	Si	828						Z 849	2.02
Al_2O_3	.90					21*				
Fe_2O_3	1.72	Al	18							
FeO	27.77									
MgO	12.69	Fe'''	22	8			11†			
CaO	3.80	Fe	386½							
Na_2O	.23	Mn	14							
K_2O	.12	Mg	314½						WXY 823½	1.96
H_2O+	1.27	Ca	68							
H_2O-	.08	Na	6	6						
TiO_2	.85	K	2	2						
MnO	.98	Ti	10½			10½				
NiO	.00	O	2524							
Li_2O	tr									
	100.13									

Analyst: E. G. Radley
Density: 3.44 (S. G. 17°C. 3.44 Hallimond)
Color hand specimen: yellow brown

$Ca_{8.5}Mg_{39}Fe_{52.5}$
% Al in Z=2.6

Indices of Refraction
*n*X 1.7137
*n*Y 1.7137
*n*Z 1.7417

Pleochroism
X, Y pale greenish brown
Z pale yellowish or reddish brown

Birefringence, x10^4 aver. 280
278, 279, 279, 280, 286

2V aver. 0°–12° in place ⊥ {010}.

Dispersion, Opt. Ax. moderate $r>v$

Z∧c aver. 39°–40°

Exsolution Lamellae, none

Remarks:

* 3 Fe^{+3} substituted for Al to balance charge.

† 5½ Fe^{+3} should go in Z group to balance charge. This analysis made in 1914 is suspected of being slightly high in Si and low in Al. It is nevertheless a very good analysis.

VISUAL ARC SPECTROSCOPIC DETECTION OF HALOGENS, RARE EARTHS AND OTHER ELEMENTS BY USE OF MOLECULAR SPECTRA[1]

Howard W. Jaffe[2]

Abstract

Cl, F, Br, Y, Sc, La, B, Al, Be, Ca and Zr may be detected in minerals by visual arc spectroscopic observation of molecular or band spectra. The versatility of the simple bunsen spectroscope is greatly enhanced through the application of molecular spectroscopy. A reference chart showing the most characteristic spectra of the visible region is included.

Introduction

The usefulness of visual-arc spectroscopy in determinative mineralogy has been described recently by Peterson, Kauffman and Jaffe.[3] The marked superiority of the spectroscopic technique over the usual blowpipe and wet reagent qualitative tests for most elements has been further emphasized by Garbriel, Jaffe and Peterson[4] and by Vreeland.[5] The methods described in these papers were concerned largely with the detection of the cationic constituents of minerals by means of atomic or line spectra. Subsequently, an investigation was made of the molecular or band spectra of the visible region in order to determine whether any additional anions could be detected by this means. The study revealed that chlorine could be readily detected in minerals by observation of the CaCl bands. It was also determined that several of the cationic constituents emit band spectra which are in some instances more useful than the line spectra of the same elements. All of the molecular spectra described in this paper are classified according to Pearse and Gaydon.[6]

General

Arc excitation of the various elements gives rise to a change of electronic state, which in turn gives rise to line spectra for excited atoms and band spectra for excited molecules. In most instances, line spectra are of sufficient abundance and intensity to serve for detecting most of the elements occurring in minerals. In the case of fluorine, chlorine, boron and other elements, it becomes necessary to resort to a study of molecular or band spectra. These elements do not provide atomic or line spectra, in the visible region, of sufficient intensity to permit their detection by normal spectroscopic procedures. They do, however, give molecular spectra which may be easily identified. Study of the band spectra of other elements that do show sensitive line spectra is also helpful in that these give the simple bunsen spectroscope a much greater versatility. For example, the only sensitive spectral lines of Al in the visible region lie at 3961.5 Å and 3944.0 Å in the violet region of the spectrum. A sensitive band resulting from AlO,[6] however, is situated in the blue green region of the spectrum, with its head at 4842.1 Å. By moving the telescope arm of the spectroscope to the blue-green region and observing the AlO band it is also possible to identify the line spectra of other elements that may be volatilizing at the same time and have spectral lines in the vicinity of the AlO band. The mineral beryl is a good example. Be and Al will volatilize at approximately the same time. Both elements give sensitive bands in the blue and blue-green region, but Be does not in the violet region. Although it is a simple matter to move the telescope arm back and forth, this may sometimes be avoided. Where trace constituents are being sought along with major constituents of like volatility, it is highly desirable to focus on one portion of the spectrum rather than to shift about, risking loss of detection of the trace constituent.

---

[1] Manuscript completed December 1948, not subject to copyright.

[2] Petrographer, Metallurgical Division, College Park Branch, Bureau of Mines, College Park, Maryland.

[3] Peterson, M. J., Kauffman, A. J., Jr., and Jaffe, H. W., The spectroscope in determinative mineralogy: *Am. Mineral.*, **32**, 322–335 (1947).

[4] Gabriel, A., Jaffe, H. W., and Peterson, M. J., Use of the spectroscope in the determination of the constituents of boiler scale and related compounds: *Proc. A.S.T.M.*, **47**, 1111–1120 (1947).

[5] Vreeland, F. K., A direct reading analytical spectroscope: *Am. Mineral.*, **33**, 600–611 (1948).

[6] Pearse, R. W. B., and Gaydon, A. G., The Identification of the Molecular Spectra: New York, John Wiley and Sons, Inc. (**1941**).

The spectroscopic assembly used in this laboratory has already been described in detail in other papers.[3,4] Inasmuch as glass prisms are employed in place of the grating, the dispersion is nonlinear. For any one arbitrary field of view, the following portions of the visible spectrum may be observed:

	Field of view	*Range covered*
Red end	±7800 to 6940Å	±860 Å
	6940 to 5520	1420
	5520 to 4830	690
	4830 to 4400	430
	4400 to 4120	280
	4120 to 3930	190
Violet end	3930 to ±3880	±50

The differences in the spectral range covered for each field of view illustrates the marked nonlinear dispersion of the prism-equipped spectroscope. The pros and cons of prism versus grating for *spectrographic* work

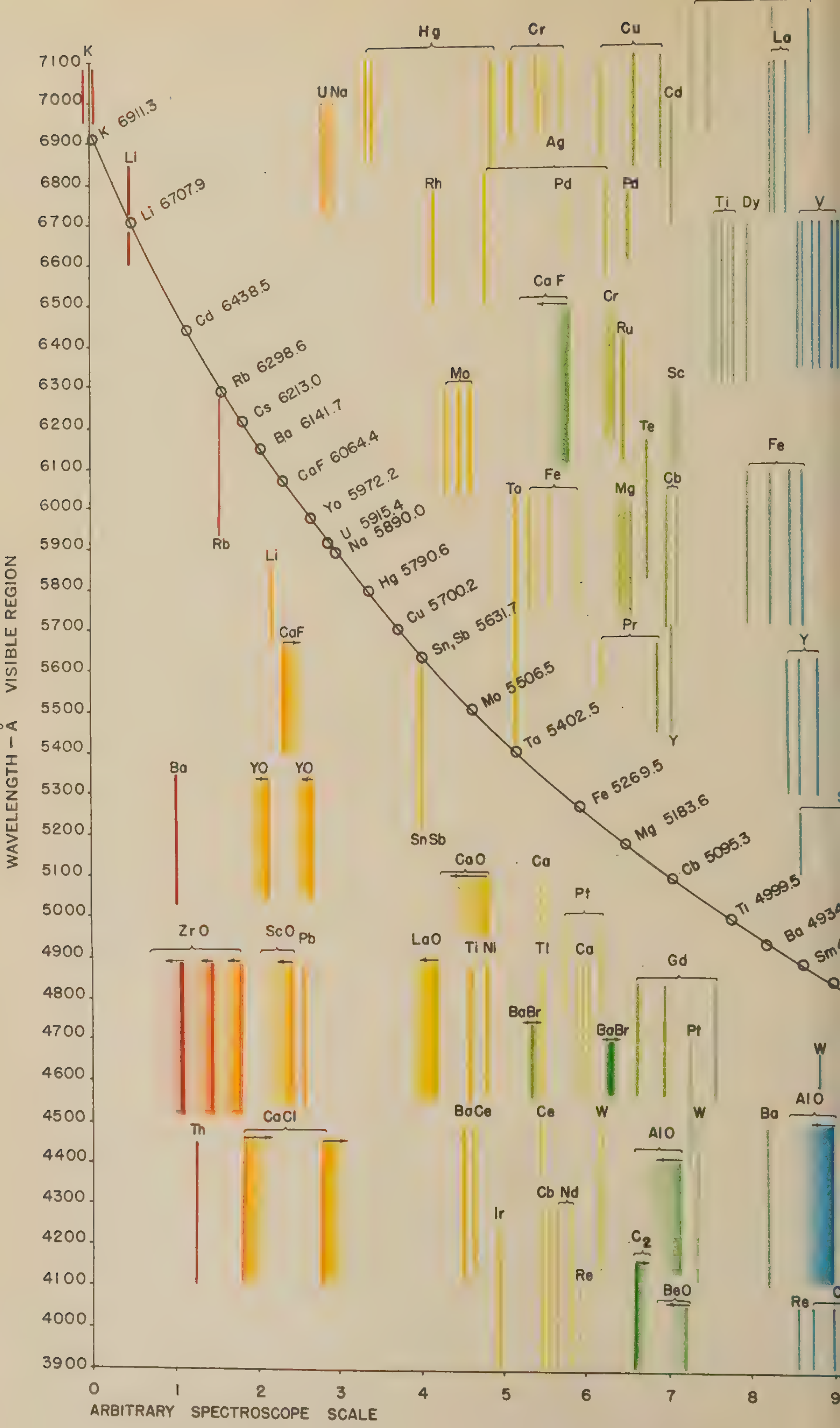
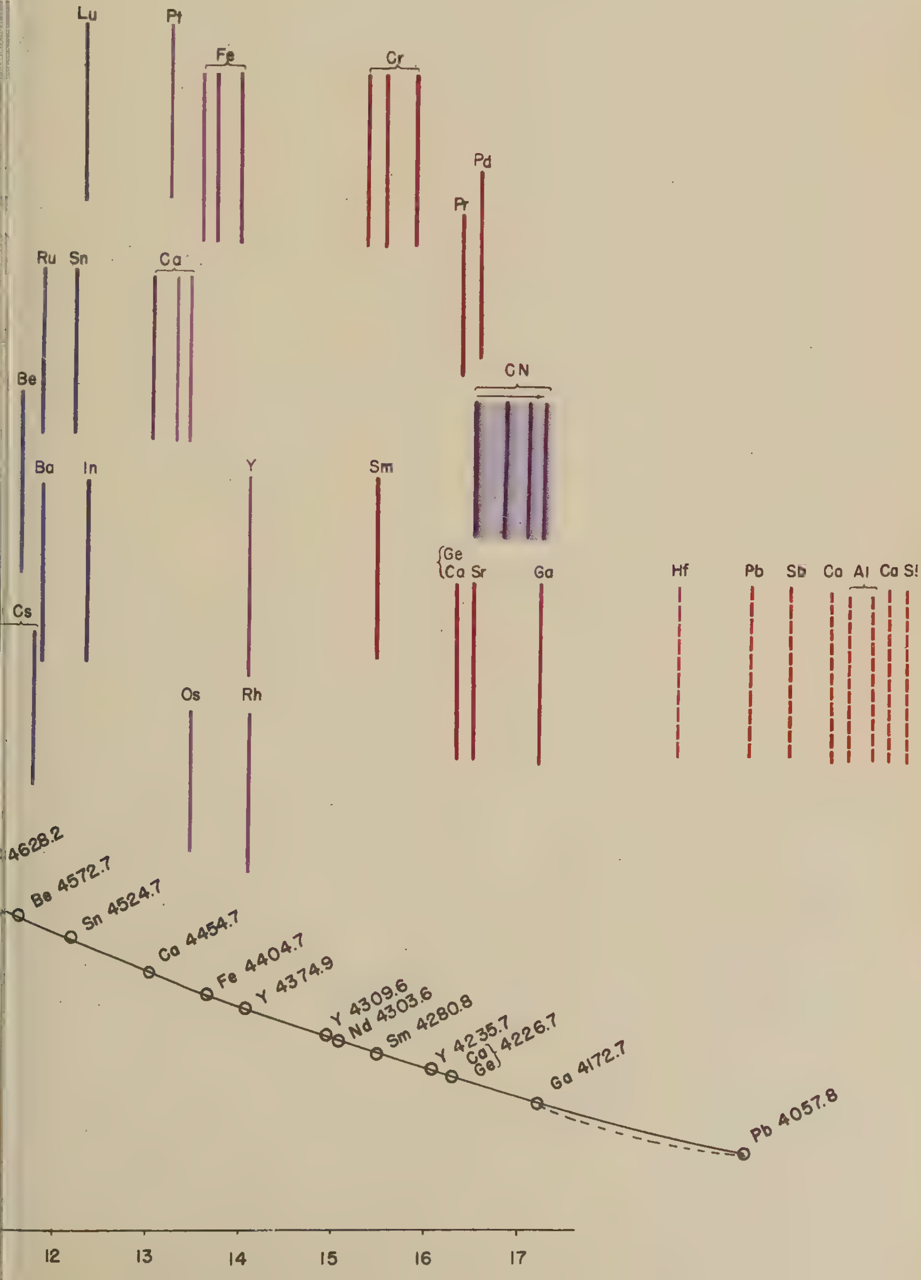

WAVELENGTH – Å VISIBLE REGION
ARBITRARY SPECTROSCOPE SCALE
7100
7000
6900
6800
6700
6600
6500
6400
6300
6200
6100
6000
5900
5800
5700
5600
5500
5400
5300
5200
5100
5000
4900
4800
4700
4600
4500
4400
4300
4200
4100
4000
3900
0
1
2
3
4
5
6
7
8
9
K
K 6911.3
Li
Li 6707.9
Cd 6438.5
Rb 6298.6
Cs 6213.0
Ba 6141.7
CaF 6064.4
Yo 5972.2
U 5915.4
Na 5890.0
Hg 5790.6
Cu 5700.2
Sn,Sb 5631.7
Mo 5506.5
Ta 5402.5
Fe 5269.5
Mg 5183.6
Cb 5095.3
Ti 4999.5
Ba 4934
Sm
Rb
Li
CaF
Ba
YO
YO
ZrO
ScO
Pb
Th
CaCl
U Na
Hg
Cr
Cu
Cd
Ag
La
Rh
Pd
Pd
Ti
Dy
V
CaF
Cr
Ru
Sc
Mo
Te
Fe
To
Fe
Mg
Cb
Pr
Y
Y
Sn Sb
CaO
Ca
Pt
LaO
Ti Ni
Tl
Ca
Gd
BaBr
BaBr
Pt
W
AlO
BaCe
Ce
W
W
Ba
AlO
Cb Nd
Ir
Re
C2
BeO
Re

Figure I LINE AND BAND SPECTRA
OBSERVED WITH A BUNSEN SPECTROSCOPE

Source of excitation.........D. C. Arc
Dispersion system.....two 60° flint glass prisms 27 x 54 mm



have been discussed elsewhere by M. Slavin.[7] For visual *spectroscopic* analysis, the advantages resulting from the use of the prism or grating vary with the nature of the problem being studied. For rapid spectroscopic analyses of minerals, the author prefers the prism-equipped instrument. When a grating is used, many of the spectral lines and bands are too spread out to be viewed rapidly by the operator. Use of the prism affords many tight groups of spectral lines and narrow bands that may be rapidly recognized. The disadvantage of the prismatic lack of resolution in the red and orange areas is negligible for this type of analysis.

Reference Chart of the Visible Spectra

To familiarize the reader with the characteristic spectra of the visible region, a reference chart (Fig. 1) has been prepared. The chart shows the most sensitive visible molecular and atomic spectra of 62 elements. For a complete description of the equipment used and the operating conditions by which these spectra were obtained, the reader is referred to "The spectroscope in determinative mineralogy"[3]. By using a reference chart of this type, the inexperienced operator can readily familiarize himself with the positions of the various lines and bands of the different elements. By laying a straightedge along any particular line or band head he may also detect the presence of any interfering lines. The most sensitive spectral bands referred to in this paper are shown in Fig. 1.

Detection of Halogens

1. Chlorine—This element may best be detected visually by observation of the CaCl bands[6] in the red-orange region with heads at 6211.6 Å. and 5934.0 Å. Both bands are degraded to the violet or shorter wavelengths. The band at 5934.0 Å. appears as a very narrow band with a bright head and is easier to detect in low Cl concentrations than the band at 6211.6 Å. Pearse and Gaydon[6] give intensities of 10 (based upon a scale of 10 for strongest band heads) for both of these bands but these are the result of spectrographic measurements rather than visual spectroscopic observations. On occasion these relative intensities may vary for several reasons. One of these is the source of excitation used; the author used only the D.C. carbon arc. Additionally, the eye sensitivity to the various colors varies, as do the photographic sensitivities of different film emulsions used in spectrographic work. In Table 1 the author has estimated the visual spectroscopic intensities of these and other bands which are offered for comparison with the intensities listed by Pearse and Gaydon.

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[7] Slavin, Morris, Prism Versus Grating for Spectrochemical Analysis: Proc. Seventh Conference on Spectroscopy (1939), John Wiley and Sons, 1940, pp. 51–58.

TABLE 1. PERSISTENT BAND HEADS* (in Carbon Arc only)

Molecule	Wavelength in Å	Direction Degraded	Intensity Spectrographic	Intensity Spectroscopic
AlO	4842.1	Red	10	10
BO	Weak, diffuse, broad bands in the green	—	—	1
BaBr	5360.1	Headless	Very weak	1
BaBr	5208.2	Headless	Very weak	1
BaCl	5240.5	Red	10	4
BaCl	5136.0	Red	10	4
BeO	5075.2	Red	7	7
BeO	4708.7	Red	10	10
CaCl	6211.6	Violet	10	9
CaCl	5934.0	Violet	10	10
CaF	6064.4	Violet	10	10
CaF	5291.0	Red	10	10
CaO	5473.0	Red	10	10
LaO	5599.9	Red	10	10
LaO	4418.1	Red	10	9
LaO	4371.9	Red	10	9
ScO	6036.2	Red	10	10
ScO	4857.8	Red	5	6
YO	6132.1	Red	10	9
YO	5972.2	Red	10	10
YO	4817.4	Red	10	10
ZrO	6473.7	Red	10	8
ZrO	6344.9	Red	9	8
ZrO	6229.4	Red	9	8

* Adapted from Pearse and Gaydon.[6]

Chlorine may also be detected by observation of the BaCl bands in the green, with heads at 5240.5 Å. and 5136.0 Å. Both bands are degraded to the red or shorter wavelengths. Both of these appear as narrow bands with fuzzy, rather indistinct heads. Pearse and Gaydon give intensities of 10 to both bands. Visually, however, both BaCl bands have an approximate intensity of 4. For visual spectroscopic detection of Cl, therefore, the CaCl bands are preferred. Other molecules containing chlorine, not studied by the author, are thoroughly described by Pearse and Gaydon.

If a calcium-free mineral is to be checked for chlorine, a small amount of CaO or any other calcium salt may be added to the unknown to produce the CaCl molecular band. (Any such salt added should, of course, first be checked spectroscopically for purity.) Chlorine has been detected by the author in vanadinite, sodalite, apatite, sylvite, halite, atacamite, calomel, pyromorphite and zunyite by observation of the two CaCl bands. The distinction of chlor-apatite from fluor-apatite is a simple one if this method is used. Such distinction can be made in less than 1 minute because both halogens volatilize very rapidly. Of five apatites examined, fluorine was a major constituent of four and a trace constituent of the other which contained major chlorine. Only one of the four fluor-apatites contained a trace of chlorine.

2. Fluorine—Visual spectroscopic detection of this halogen by observation of the yellow-green CaF band has previously been described by Peterson, Kauffman, and Jaffe[3] and more recently by Jaffe.[8] Spectrographic studies of this band were made by Papish, Hoag, and Snee,[9] Pearse and Gaydon,[6] Ahrens,[10] and others. This band has its head at 5291.0 Å. and is degraded to the longer wavelengths. It is a broad band which culminates in a very sharp head rendering its detection a very simple matter. Less than 0.1 per cent of fluorine may be detected by visual observation of this very sensitive band. A second CaF band of equal prominence and sensitivity occurs in the red-orange region with its head at 6064.4 Å. This band is rather narrow, has a sharp head and is degraded to the shorter wavelengths. It may be used as an alternate when detection of the alkalies is being sought. Na, K, and Rb have their sensitive lines in this same portion of the visible region and like CaF, volatilize very rapidly. Both of the CaF bands appear to be brighter than those of any other molecule observed. To determine fluorine in calcium-free minerals, as with chlorine determinations, any pure salt of calcium may be added to the unknown.

3. Bromine—The only bands observed were those of the BaBr molecule.[6] These occur in the yellow-green region with heads at 5360.1 Å. and 5208.2 Å. Both are very weak visually and do not show well-defined heads. Because of their poor sensitivity, they will not prove very useful for visual arc spectroscopic analysis of minerals.

4. Iodine—Although many molecules of this halogen give band spectra,[6] none were observed in the visible region using the carbon arc as the source of excitation.

Detection of Rare Earths

1. Yttrium—Although this element has several sensitive lines in the visible region, knowledge of its band spectra has proved useful, particularly when only a trace of this element is present. Yttrium is relatively

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[8] Jaffe, H. W., Reexamination of sphene (titanite): *Am. Mineral.*, **32**, 638 (1947).

[9] Papish, J., Hoag, L. E., and Snee, W. E., Spectroscopic detection of fluorine: *Ind. and Eng. Chem.*, **2**, No. 3, 263–264 (1930).

[10] Ahrens, L. H., The spectrochemical determination of fluorine in phosphate rock: *J. S. African Chem. Inst.*, **25**, 18–32 (1942).

refractory and one of the last elements to volatilize in some minerals. Where a spectroscopic trace is present, the atomic line and molecular band spectra will flash intermittently, particularly if the amperage is kept low. When only a few such flashes are to be observed, the broad conspicuous YO bands are easier to see than any of the Y lines. By observation of the YO bands in the red-orange region, the author can detect the yttrium commonly present in apatites; normally less than 0.5 per cent of Y_2O_3. In other minerals, it has been detected in concentrations as low as 0.01 per cent.

Bands resulting from the YO molecule[6] occur in the red-orange region with heads at 6132.1 Å. and 5972.2 Å. A third band with a head at 4817.4 Å. is situated in the blue. All three bands are degraded to the red or longer wavelengths. Inasmuch as many other refractory elements have lines and bands in the blue, especially titanium, it is better to use the red-orange bands in order to avoid interference.

2. Scandium -Although this element may not be as prevalent in minerals as other rare earths, a knowledge of its molecular spectra may prove helpful. Bands of ScO[6] occur in the red-orange and in the blue with heads at 6036.2 Å. and 4857.8 Å., respectively. Both are degraded to the longer wavelengths. The intensities favor the use of the red-orange band. Scandium has been observed in some micas, tourmalines and garnets where it occurs in concentrations of less than 0.1 per cent of Sc_2O_3.

3. Lanthanum—This element has three LaO bands[6] all degraded to the longer wavelengths. They culminate in relatively sharp heads at 5599.9 Å., 4418.1 Å. and 4371.9 Å. These are useful when the very sensitive La doublet at 4921.8 Å. and 4921.0 Å. is covered by interference from Fe or other lines. Lanthanum traces have been detected by the author in several apatites, where it commonly occurs in concentrations of less than 0.1 per cent of La_2O_3.

Cerium, praesodymium, samarium, neodymium and erbium all have spectral lines that are more conspicuous than any molecular bands observed. The author has not studied the other rare earths in any detail due to the difficulty of obtaining uncontaminated salts.

Other Useful Band Spectra

1. Aluminum—The utility of the AlO band in the blue-green region has been discussed in the "General" section of this paper. It is a broad band, culminating in a sharp head at 4842.1 Å., and is degraded to the red. Other less sensitive bands occur in the green spectral region.

2. Boron —This element does not show any bright or conspicuous band heads in the visible region. It does, however, have a series of broad diffuse

bands which cloud the entire green region of the spectrum in a characteristic manner. This is attributed to the BO molecule.[6] The veiled appearance, its early volatility and the green arc image color are diagnostic. Traces of boron cannot be detected visually but the element is readily detectable in tourmaline, axinite and other boron minerals.

3. Beryllium—This element has but one atomic spectral line in the visible region, at 4572.7 Å., which is usable. When this line is covered by interference, the BeO bands[6] in the blue-green region are indispensable alternates. These have band heads at 5075.2 Å. and 4708.7 Å. Both are degraded to the longer wavelengths.

4. Calcium—This element has a very complicated system of CaO bands[6] in the red-orange region. They are bright bands but overlap and for this reason are not too easily identified visually. A broad band in the yellow-green is easier to detect and is sometimes useful. The band head is at 5473.0 Å and is degraded to the red. It is interesting to note that, when a sample of fluorite is volatilized in the carbon arc, lines of Ca, bands of CaF and bands of CaO are all readily discernible. In apatites, the CaCl bands may also be present at the same time.

5. Zirconium—This element gives a very complex line spectrum in the visible region. The strong lines in the blue, however, are sometimes interfered with by lines of titanium, molybdenum and other refractory elements. Because of this, a trio of ZrO bands[6] in the red are on occasion helpful. These culminate in distinct heads at 6473.7 Å., 6344.9 Å. and 6229.4 Å. All are degraded to the longer wavelengths.

6. Thorium—Pearse and Gaydon[6] and other reference books do not list any molecular spectra of which thorium is a constituent. However, the element has a number of lines lying between 6408.6 Å. and 6416.1 Å. in the red portion of the spectrum. These lines are not resolved and are seen as a conspicuous narrow "band." The author has found this "band" to be more sensitive visually than any of the four individual thorium lines in the green and blue spectral region. Inasmuch as this element often occurs in minerals containing appreciable amounts of rare earths, which are of like volatility, it is difficult to detect the Th lines in the green and blue region. For example, lines of Ce, La, Y and Nd commonly interfere with the detection of thorium. By use of the "band" in the red region, however, the operator can avoid the otherwise serious effects of interfering lines. Thus far, thorium has been detected in every monazite examined, by observation of the "band." It could not be detected in several of these by use of other line spectra. The thoria content of different monazites, however, shows a marked variation.

The thorium lines are not nearly so sensitive as those of the rare earths and trace amounts cannot be detected by visual spectroscopy.

CONCLUSIONS

1. In visual spectroscopic work, F, Cl, Br and B may be identified in minerals only by observation of molecular or band spectra.

2. Molecular spectra are in some instances more useful than atomic or line spectra for the detection of some elements by means of visual arc spectroscopy. (E.g., the YO bands appear to be more sensitive than the Y lines.)

3. Where spectral lines of one element are hidden by interfering lines of another element, a knowledge of band spectra is indispensable. (E.g., use of the BeO bands when the only usable Be line is hidden.)

ACKNOWLEDGMENT

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THE NATURE OF LATTICE EXPANSION AND ITS RELATION TO HYDRATION IN MONTMORILLONITE AND VERMICULITE

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Abstract

Expansion of the interlayer space of montmorillonite and vermiculite, brought about by hydration, takes place in steps equivalent to monomolecular layers of water. The extent of expansion, however, for a given number of monomolecular layers depends on the manner of packing of the water molecules.

It is suggested that the manner of packing of the water molecules in montmorillonite changes during the course of hydration from a loose and discontinuous one, at low states of hydration, to a compact and continuous manner at high states of hydration. It was therefore concluded that it is not necessary to assume interleaving of lattice layers with different degrees of hydration to explain certain variations in interlayer distances.

One of the characteristic properties of the crystal lattices of vermiculite, montmorillonite, and related clay minerals is the ability to expand or contract along the *c* axis upon hydration or dehydration. The manner of expansion has been studied by means of *x*-ray measurements of materials at various degrees of hydration.

Studies with Montmorillonite

Hendricks and Jefferson (5) have concluded that expansion of the montmorillonite lattice by hydration takes place in monomolecular layers of water and suggested that certain observed (*d*001) spacings which deviate from that caused by the absorption of a monomolecular layer of water may be accounted for by interleaving of lattices having different degrees of expansion—a condition quite possible at certain states of hydration. This view is also supported by Mering (9).

It is not always necessary, however, to assume interleaving to explain the observed variations in (*d*001) spacing. These variations may be explained by the manner of packing of the water molecules in the interlayer space.

An evaluation of the interlayer expansion due to differences in packing of the water molecules yields the following results: If the centers of the oxygens of the water molecules are vertically above and below the centers of the oxygens of the lattice, the expansion of the layers would be the maximum that could be caused by the absorption of the water molecule, namely, 2.76 Å. (2), but if the water molecules form tetrahedra with the bases of the linked silica tetrahedra of the lattice—as indicated in Fig. 1 by *a*, *b*, *c*, *d*, *e*, *f*—the expansion of the layers will only be 1.78 Å.

The thickness of the expanded unit cells—equivalent to the (*d*001) spacing—may be calculated by adding the thickness of a single mica sheet—i.e., of the four layers of oxygens which form the sheet—and the calculated expansion for one, two, or three monomolecular layers of water. The thickness of a single mica sheet for the present discussion will be taken to equal about 10.16 Å.

The thickness, therefore, of a unit cell containing one monomolecular layer of water may be either (*a*) 10.16 Å.+2.76 Å=12.92 Å or(*b*) 10.16 Å+1.78 Å=11.94 Å.

The interlayer spacing when two monomolecular layers of water are present will depend not only on the manner of superimposition of the water molecules on the oxygen sheets of the lattice but also on the manner of superimposition of one monomolecular layer of water on the other. Such consideration leads to at least three thicknesses: namely,

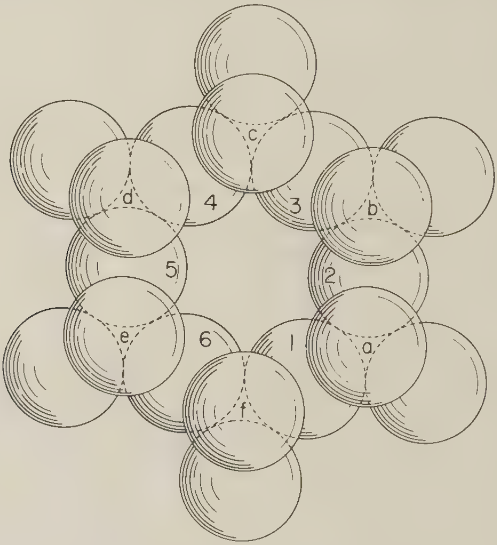

FIG. 1. Possible arrangement of water molecules in the interlayer space of montmorillonite and vermiculite.

(a) When the water molecules form tetrahedra at the water-oxygen interface and octahedra at the water-water interface; such an arrangement would give a thickness of

$$10.16 \text{ Å}+1.78 \text{ Å}+2.09 \text{ Å}=14.03 \text{ Å}.$$

(b) When the water molecules form tetrahedra at the water-oxygen interface but are vertically above each other at the water-water interface; such an arrangement would lead to a thickness of

$$10.16\ \text{Å}+1.78\ \text{Å}+2.76\ \text{Å}=14.70\ \text{Å}.$$

(c) When the water molecules are vertically above and below the oxygens of the lattice at the water-oxygen interface and are also vertically above each other at the water-water interface; such an arrangement would give a thickness of

$$10.16\ \text{Å}+2.76\ \text{Å}+2.76\ \text{Å}=15.68\ \text{Å}.$$

Similarly three thicknesses for the unit cell may be calculated when three monomolecular layers of water are present: namely, (*a*) 16.12, (*b*) 17.46, and (*c*) 18.44.

For a clearer understanding of the nature of the expanison of montmorillonite in water it is necessary to compare the relation between the expansion and the degree of hydration which may exist and those which were actually observed.

The degree of hydration in terms of per cent water per 100 grams of either ignited material or material which contains only crystal lattice OH^- ions, was calculated for a Ca saturated montmorillonite containing one or more monomolecular layers of water.

The chemical formula for a dehydrated half unit cell used in the calculation was obtained from the chemical composition and is as follows:

$$Ca_{0.25}(Al_{1.40}Fe_{0.10}Mg_{0.50})Si_4O_{11}.$$

The calculations were carried out for the following moisture conditions:

(1) Only crystal lattice water present (OH^- ions), namely, 1 H_2O per half unit cell.

(2) Enough water molecules to fill each hexagonal cavity in the oxygen rings of the linked silica tetrahedra not occupied by an exchangeable ion. The total number of water molecules for half unit cell for this condition is equal to 1.75. Since no water molecules in the form of a layer were assumed to be present, the lattice would remain contracted.

(3) Enough water molecules for conditions (1) and (2), namely, 2.75.

(4) One layer of water molecules:

   (*a*) Water molecules organized into hexagonal rings in the same manner as the oxygens at the vertices of the silica tetrahedra (Fig. 1—*a, b, c, d, e, f*). The number of water molecules in such a layer per half unit cell would be 2.

   (*b*) Water molecules arranged in hexagonal rings in the same manner as the oxygens of the bases of the linked silica tetrahedra (Fig. 1—1, 2, 3, 4, 5, 6). The number of water molecules in such a layer per half unit cell would be 3.

TABLE 1. CALCULATED PER CENT WATER CONTENTS AND (*d*001) BASAL SPACINGS FOR A CA-SATURATED MONTMORILLONITE WITH 0, 1, 2, OR 3 MONOMOLECULAR LAYERS OF WATER

Column No.	1	2	3	4	(4+3)	5	(5+3)	6	(6+3)	7	(7+3)	8	(8+3)	9	(9+3)	10	(10+3)	11	(11+3)
Number of monomolecular layers of water	none			one						two						three			
Possible (*d*001) basal spacings	10.16 Å			11.94 Å, 12.92 Å						14.03 Å, 14.70 Å, 15.68 Å						16.12 Å, 17.46 Å, 18.44 Å			
Number of H_2O molecules per half unit cell ($11.O^{=}$)	1	1.75	2.75	2	4.75	3	5.75	4	6.75	4	6.75	6	8.75	8	10.75	9	11.75	12	14.75
Per cent water content on ignited material	5.08	8.89	13.97	10.16	24.13	15.24	29.21	20.32	34.29	20.32	34.29	30.48	44.45	40.64	54.61	45.72	59.69	60.96	74.93
Number of H_2O molecules per half unit cell ($12.O^{=}$)	1	1.75	1.75	2	3.75	3	4.75	4	5.75	4	5.75	6	7.75	8	9.75	9	10.75	12	13.75
Per cent water content on material containing OH^- ions	4.84	8.47	8.47	9.68	18.15	14.52	22.99	19.36	27.83	19.36	27.83	29.04	37.51	38.72	47.19	43.56	52.03	58.08	66.55

(*c*) Water molecules arranged in hexagonal rings as in (*b*) with an additional water molecule in the center of each ring making a total of 4 water molecules per half unit cell.

(5) Two monomolecular layers of water:
  (*a*) With 2 molecules per layer or 4 per half unit cell.
  (*b*) With 3 molecules per layer or 6 per half unit cell.
  (*c*) With 4 molecules per layer or 8 per half unit cell.

(6) Three monomolecular layers of water:
  (*a*) With 3 molecules per layer or 9 per half unit cell.
  (*b*) With 4 molecules per layer or a total of 12 water molecules per half unit cell.

The results of calculation on the basis of the foregoing assumptions are given in Table 1. These results indicate that (1) a considerable amount of water may be present even in a contracted lattice, and (2) the amount of of water present for any one degree of expansion is not necessarily a constant quantity but depends on the manner of the organization of the water layer.

The results obtained by several investigators (3, 6, 7, 8, 10), on the relation between hydration and expansion of montmorillonite are summarized in Table 2.

A comparison between the data in Tables 1 and 2 reveals the following:

(1) Expansion equivalent to one or two monomolecular layers of water

TABLE 2. A SUMMARY OF DATA CONCERNING THE RELATION BETWEEN HYDRATION AND EXPANSION IN Ca OR Ca AND Mg SATURATED MONTMORILLONITES

Hofman and Bilke (7)		Maegdefrau and Hofmann (8)		Nagelschmidt (10)		Bradley, Grim and Clark (3)		Hendricks, Nelson and Alexander (6)	
H_2O on ignition bases %	(*d*001) basal spacing Å	H_2O on ignition bases %	(*d*001) basal spacing Å	H_2O on ignition bases %	(*d*001) basal spacing Å	H_2O on ignition bases %	(*d*001) basal spacing Å	H_2O on material with OH water %	(*d*001) basal spacing Å
				6.0	10.5	5.0	9.6		
				8.5	11.6			3.5	12.8
10.0	11.25			10.9	12.3			12.0	13.2
13.9	12.1	13	11.88	14.8	14.7			15.0	14.4
19.5	13.4	20	13.48	19.1	14.8	20.0	12.4	19.0	14.6
24.2	14.6			25.0	15.2			26.0	14.8
29.5	15.1	29	15.15	30.6	15.2			32.0	15.4
36.3	15.6	37	15.70	35.5	—	37.0	15.4		
41.8	15.7			42.3	15.4				
				44.9	15.4			46.0	15.7
59.0	17.8			56.2	15.6	50.0	18.4		
		65	18.90	75.4	18.3				
				104.0	18.4				

may take place at moisture contents far less than the amounts required to form continuous water layers arranged in hexagonal rings of even two water molecules (Fig. 1—*a*, *b*, *c*, *d*, *e*, *f*) per layer.

(2) The expansion beyond the equivalent thickness of two monomolecular layers of water does not take place until two continuous monomolecular layers of water are formed consisting of either hexagonal rings with three molecules per layer (3, 6) or layers of closely packed water molecules, i.e., layers of hexagonal rings with water molecules in their centers.

(3) The third monomolecular layer also consists of closely packed water molecules.

(4) The range in values of the basal spacing, (*d*001), between about 11.8 to 13.0 Å, between 14.0 to 15.7 Å, or between 16.0 to 18.4 Å. may be explained on the manner of packing of the water molecules between the oxygen sheets of the lattice. At low moisture contents apparently the monomolecular layers are discontinuous and the water molecules tend to form tetrahedra with the bases of the linked silica tetrahedra. This type of packing results in the smallest observed expansions. However, as the water content increases the water molecules seem to form more closely packed layers consisting of hexagonal rings similar to the hexagonal rings of the linked silica tetrahedra (Fig. 1—1, 2, 3, 4, 5, 6) and are superimposed on the oxygen rings of the silica tetrahedra in such a manner as to result in the wider spacings.

Studies with Vermiculite

Recent investigation (1) on the nature of vermiculite has shown that vermiculite is essentially a mica in which Mg, or Mg plus Ca, are the interlayer cations like K in ordinary mica, but having an expanded and hydrated lattice similar to that of montmorillonite. As in montmorillonite Mg and Ca ions exchange readily with other cations in solution. The exchange capacity of vermiculite is about 50 per cent higher than that of montmorillonite.

The contraction or expansion of the vermiculite lattice, whether brought about by base exchange, by heating, or by immersion in water (Table 3), also indicates that it takes place in steps each equivalent to a thickness of one molecular layer of water.

The interlayer spacing of air dried vermiculite lattice was shown to depend on the exchangeable ion. Thus the crystal lattices saturated with K, NH_4, Rb, or Cs ions are essentially contracted lattices. The lattices saturated with Li, Na, or Ba ions are expanded to a thickness equivalent to a monomolecular layer of water; and those saturated with Mg or Ca

Table 3. The Relation Between Hydration and Expansion in Vermiculate #2 (1)

Saturating cation	Mg		Ca		Na	
	H_2O on ignition bases %	(*d*002) basal spacing Å	H_2O on ignition bases %	(*d*002) basal spacing Å	H_2O on ignition bases %	(*d*002) basal spacing Å
Air dried	27.10	14.33	27.80	15.07	19.51	12.56
Heated to 150° C.	10.75	11.77	11.31	11.77	9.36	10.27
Heated to 250° C.	7.38	10.34	7.89	10.20	6.77	10.13
Heated to 550° C.	5.83	10.00	6.20	10.00	5.87	10.00
Heated to 750° C.	0.00	9.50	0.00	9.65	0.00	9.60
Immersed in water	>100	14.47	>100	15.41	>100	14.76

ions are expanded to a thickness equivalent to two monomolecular layers of water (1).

The amount of water found in natural vermiculites, i.e., Mg or Mg plus Ca saturated, is equal to about 4 molecules per half unit cell (1, 4). This amount of water, as was indicated previously, is only sufficient to form two monomolecular layers of water consisting of hexagonal rings similar to the hexagonal rings of oxygens at the vertices of linked silica tetrahedra (Fig. 1—*a*, *b*, *c*, *d*, *e*, *f*). The basal spacing (*d*002) found, namely 14.33, tends to confirm this type of organization of the water molecules. For, as was shown previously, such a basal spacing can be obtained only when the water molecules are at the vertex of each linked silica tetrahedron.

The interlayer spacing of vermiculite when immersed in water* is reported in Table 3. It is seen that the interlayer spacing of the Mg saturated sample remained unchanged, that of the Ca saturated sample changed only slightly, but the interlayer spacing of the Na saturated sample changed very markedly with hydration. The change in the spacing of the Ca vermiculite possibly represents a reorganization of the water molecules from a configuration as indicated by *a*, *b*, *c*, *d*, *e*, *f*, of Fig. 1 to a configuration indicated by 1, 2, 3, 4, 5, 6, of Fig. 1. The change in the spacing of the Na vermiculite clearly represents an expansion equivalent to a monomolecular layer of water.

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* To obtain *x*-ray diagrams of material immersed in water, the sealed ends of capillary tubes packed with air dried material were broken off and immersed in water. After the samples became saturated with water by capillarity the two ends of the tube were sealed with De Khotinsky cement to prevent water loss during exposure to *x*-rays.

The manner of contraction of vermiculite upon dehydration (Table 3) clearly shows that the contraction is also in steps equivalent to monomolecular layers of water.** These results also indicate that, as in montmorillonite, the lattice of the Ca or Mg vermiculite remains expanded to a thickness equivalent to a monomolecular layer at moisture contents which are far below the amount of water necessary to form a continuous water layer of even two water molecules per layer in half unit cell. The contraction which takes place between 550° to 700° has been discussed previously (1).

INTERLEAVING

One sample of vermiculite studied clearly demonstrates the effect of interleaving of expanded and contracted lattices. This sample consisted of biotite and vermiculite and was first described by Gruner (4) as a "hydrobiotite," from Libby, Montana. Base exchange studies (1) have shown that this sample consisted of 75% biotite and 25% vermiculite and that the vermiculite and biotite are interleaved in the proportion of three biotite sheets to one vermiculite sheet.

According to Hendricks and Jefferson (5) such an interleaved material when exposed to *x*-rays should show a basal spacing (*d*001) which is an average of the basal spacing of each material and that the *x*-ray line representing the resulting basal spacing should be broad. In the sample studied the average basal spacing should therefore be $(3\times 10.45+1\times 15.07)\div 4=11.7$ Å (10.45 Å is the biotite basal spacing of this sample and 15.07 is the vermiculite basal spacing) and the reflection should be represented by a broad line. The spacing actually obtained was 11.77 Å and the line representing this spacing was about 3 mm. broad. These results therefore substantiate Hendricks and Jefferson's conclusion.

However, interlayer spacing of powdered samples which consist of crystals with varying degrees of expansion are not necessarily average spacings. An average spacing apparently results only if the lattices are interleaved in a regular pattern as was shown to be the case in the "hydrobiotite" from Libby, Montana. If the crystal lattices with different

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** The author noted previously (1) that vermiculite rehydrates very rapidly after dehydration even when cooled in a desiccator containing $CaCl_2$. This rapid rehydration was given as the reason for obtaining both expanded and contracted lattices in samples which were heated moderately. It is for the same reason, perhaps, that Gruner (4) was unable to observe any contraction in vermiculites until heated to 700° C.

To overcome rehydration upon cooling and exposure to air while being prepared for *x*-ray analysis, the samples were packed in capillary glass tubing in the oven at the heating temperatures, namely 150° C. and 250° C. Samples, however, which were heated at 500° C. were transferred for packing to another oven at 250° C. To prevent rehydration during exposure to *x*-ray, the glass tubes were sealed with De Khotinsky cement as soon as filled.

degrees of expansion are separate entities and are merely mixed at random, a basal spacing for each lattice will be observed upon the *x*-ray diffraction pattern of the sample. An example of such a mixture was obtained in partially rehydrated vermiculite samples (1). It seems that in these samples the extremely small particles were completely rehydrated but the coarser ones remained dehydrated.

Expansion Other than in Monomolecular Layers of Water

Expansion of a lattice other than in steps equivalent to a thickness of monomolecular layers of water was demonstrated by NH_4, Rb and Cs vermiculites (1). In these vermiculites the expansion of the lattice is believed to be brought about by the large dimensions of the exchangeable ions which presumably occupy the centers of the hexagonal oxygen rings of the linked silica tetrahedra of one mica sheet and water molecules which occupy similar cavities right across from the exchangeable ions in the opposite mica sheets. Since the diameters of these exchangeable ions are larger than the diameter of the cavities which they occupy, they protrude above the plane of the oxygen sheets of the lattice and this gives a correspondingly wider spacing. The amount of expansion was found to be proportional to the difference in dimension between the size of the ion and the size of the cavity which it occupies.

Conclusions and Summary

The expansion or contraction parallel to the (001) plane of the crystal lattice of montmorillonite and vermiculite brought about by hydration, dehydration, or by base exchange, seems to take place in steps equivalent to a thickness of monomolecular layers of water. It was suggested that an explanation for the variation of the interlayer space for a given number of monomolecular layers of water may be found in the manner of packing of the water molecules in the interlayer space.

In Ca and Mg montmorillonite and vermiculite expansion equivalent to one or two monomolecular layers takes place at very low states of hydration.

In montmorillonite expansion beyond the equivalent of two monomolecular layers of water apparently does not take place until each of the two layers consists of at least three water molecules per half unit cell and the layers cover the entire interlayer surface. In vermiculite expansion beyond the equivalent of two monomolecular layers of water was never observed to take place even when samples were immersed in water.

The water molecules in montmorillonite at relatively low states of hydration and in natural vermiculite tend to form tetrahedra with the bases of the linked silica tetrahedra of the lattice. This type of packing gives rise to hexagonal rings of water molecules which are similar to the hexagonal rings of oxygens at the vertices of the linked silica tetrahedra of the individual mica sheets (Fig. 1—*a*, *b*, *c*, *d*, *e*, *f*).

At high states of hydration the water molecules in montmorillonite tend to form hexagonal rings of water molecules which are similar to the hexagonal rings of the oxygens at the bases of the linked silica tetrahedra (Fig. 1—1, 2, 3, 4, 5, 6), as suggested by Hendricks and Jefferson (5). At very high states of hydration even the centers of these hexagonal water rings, and the centers of the hexagonal oxygen rings of the linked silica tetrahedra not occupied by exchangeable ions seem to be filled with water molecules. Such monomolecular layers of water consist of closely packed water molecules and bring about the widest possible expansion of the lattice layers.

The interleaving of vermiculite and biotite clearly demonstrates the effect of interleaving of expanded and contracted lattice layers on the (*d*002) basal spacing as measured by *x*-ray diffraction patterns. The basal spacing obtained for such interleaved material supports Hendricks and Jefferson's conclusion (5) that in this case the interlayer spacing is an average with broad *x*-ray lines.

REFERENCES

(1) BARSHAD, I., Vermiculite and its relation to biotite as revealed by base exchange reactions, *x*-ray analyses, differential thermal curves, and water content: *Am. Mineral.*, **33**, 655–678 (1948).

(2) BERNAL, J. D., AND FOWLER, R. H., A theory of water and ionic solution, with particular reference to hydrogen and hydroxyl ions: *Jour. Chem. Phys.*, **1**, 515–548 (1933).

(3) BRADLEY, W. F., GRIM, R. E., AND CLARK, W. L., A study of the behavior of montmorillonite upon wetting: *Zeit. Krist.*, **97**, 216–222 (1937).

(4) GRUNER, J. W., The structure of vermiculites and their collapse by dehydration: *Am. Mineral.*, **19**, 557–574 (1934).

(5) HENDRICKS, S. B., AND JEFFERSON, M. E., Structure of kaolin and talc pyrophyllite and their bearing on water sorption of clays: *Am. Mineral.*, **23**, 863–875 (1938).

(6) HENDRICKS, S. B., NELSON, R. H., AND ALEXANDER, L. T., Hydration mechanism of the clay mineral montmorillonite, saturated with various cations: *Am. Chem. Soc. Jour.*, **62**, 1457–1464 (1940).

(7) HOFMANN, U., AND BILKE, W., Über die innerkristalline Quellung und das Basenaustauschvermogen des Montmorillonits: *Kolloid-Zeits.*, **77**, 238–251 (1936).

(8) MAEGDEFRAU, E., AND HOFMANN, U., Die Kristallstruktur des Montmorillonits: *Zeit. Krist.*, **98**, 299–324 (1937).

(9) MERING, J., On the hydration of montmorillonite: *Trans. Faraday Soc.*, **42B**, 205–219 (1946).

(10) NAGELSCHMIDT, G., On the lattice shrinkage and structure of montmorillonite: *Zeits. Krist.*, **93**, 481–487 (1936).

SCORZALITE FROM SOUTH DAKOTA: A NEW OCCURRENCE[1]

W. T. PECORA AND J. J. FAHEY

ABSTRACT

The occurrence, mineral association, chemical analysis, and physical properties of scorzalite, $(Fe'', Mg)Al_2(PO_4,)_2(OH)_2$, from the Victory mine near Custer, S. Dak., are described. Scorzalite from this locality—the second reported occurrence of this mineral—has a Fe:Mg molecular ratio of 3:1, is richer in iron and has a higher specific gravity and higher indices of refraction than the type scorzalite from Minas Gerais recently described by the same authors.

INTRODUCTION AND ACKNOWLEDGMENTS

In September 1947, during a visit with U. S. Geological Survey field parties under the direction of L. R. Page in the Black Hills of South Dakota, the senior author acquired a blue mineral specimen which he later identified as scorzalite, the ferrous-iron member of the lazulite-scorzalite isomorphous series. Because of the similarity of the material to the type scorzalite from Minas Gerais, Brazil, the authors made a detailed study of the mineral from this new locality. M. H. Staatz and J. W. Adams kindly collected a large number of specimens from the dump of the Victory mine—the source of the first specimen examined.

The writers are grateful to a number of their colleagues in the Section of Geochemistry and Petrology, U. S. Geological Survey, for assistance in various stages of the investigation.

OCCURRENCE

The Victory pegmatite mine is located about 2 miles northeast of Custer, Custer County, S. Dak. In 1943–44 this mine was one of the outstanding producers of sheet muscovite in the United States. L. R. Page, who observed the mineral occurrence during mining operations, reports the following account (personal communication):

"The blue mineral now identified as scorzalite was seen in place only on the 120-foot level, about 20 feet west of the intersection with the crosscut from the mainshaft. Most of the rock containing scorzalite was excavated during mining operations for mica. The lower levels of the mine are inaccessible at the present time and specimens of the mineral can be obtained only from the dump.

"Mica-bearing pegmatite at the Victory mine is internally divided into a 'wall zone' (composed essentially of blocky plagioclase, quartz, and muscovite) and a 'core' (of perthite and quartz). Scorzalite was found principally in the wall zone, but some grains were also observed in the granulite developed from schist where the two main pegmatites on the 120-foot level merge discordantly. Triphylite is the only other phosphate mineral noted in the pegmatite and it is concentrated in the wall zone with black tourmaline and ruby muscovite."

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[1] Published by permission of the Director, U. S. Geological Survey. Paper read before the November 1948 annual meeting of the Mineralogical Society of America.

Descriptive Mineralogy

In the dozens of hand specimens available, scorzalite occurs only in pegmatite with quartz, plagioclase, muscovite, tourmaline, and triphylite. The scorzalite is massive and so intimately intergrown with tourmaline, triphylite, and muscovite that small fragments, one centimeter

Table 1. Chemical Analyses and Physical Properties of Scorzalite from South Dakota and Minas Gerais
(Analyses by J. J. Fahey)

	Victory mine South Dakota	Corrego Frio Minas Gerais[1]
Al_2O_3	30.80	30.87
Fe_2O_3	0.13	0.54
TiO_2	0.10	0.10
FeO	17.06	14.74
MgO	2.93	4.23
MnO	0.10	0.11
ZnO	—	0.17
CaO	0.03	0.02
P_2O_5	42.67	42.90
H_2O+	6.10	5.86
Totals	99.92	99.54
Mol. ratio, Fe'':Mg.	76:24	66:34
Sp. gr.[2] (± .005)	3.327	3.268
α (colorless)	1.636	1.633
β (blue)	1.666	1.663
γ (blue)	1.676	1.673
2V (calculated)	61° (−)	62° (−)
Cleavage	(110); good	(110), good
Orientation	Z=*b*; X near *c*	Z=*b*; X near *c*
Twinning	multiple	multiple

[1] For original description see Pecora and Fahey, *Am. Mineral.*, 34, 83–93 (1949).
[2] Determined with a fused quartz Adams-Johnston pycnometer.

across, are rarely free from admixed minerals. Powdered scorzalite can be purified using a heavy liquid (methylene iodide) and the electromagnetic separator.

The chemical analysis and physical properties of scorzalite from the Victory pegmatite are listed in Table 1, where they are compared with those of scorzalite from Minas Gerais. The Victory scorzalite has a higher molecular ratio of $Fe'':Mg$, higher specific gravity, and higher indices of refraction. X-ray powder patterns of scorzalite and lazulite are identical.

A brief description of the associated minerals is given below:

Tourmaline: massive and stubby, faceted crystals; color, black; $\omega = 1.655$; $O =$ dark-gray green; specific gravity, 3.16.

Triphylite: massive; color, dark green; $\beta = 1.690$; 2V, very large; $Y =$ blue green.

Plagioclase: massive, coarsely twinned; composition almost pure albite; $\beta = 1.533$.

Muscovite: two conspicuous varieties, ruby and yellow; in zoned plates, the ruby mica forms the core; the yellow mica also forms aggregate plates that are younger in age sequence than the ruby variety and the scorzalite; β (ruby) $= 1.592$; β (yellow) perceptibly lower than that of the ruby variety.

AN INEXPENSIVE PETROGRAPHIC MICROSCOPE[1]

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ABSTRACT

A number of manufacturers have recently announced development of students' microscopes selling for about $100.00, which can be adapted for elementary petrographic work by the addition of inexpensive polaroid elements, and a simple rotating stage. The design of a stage and installation of polaroids are described.

POLARIZING ELEMENTS

Conventional petrographic microscopes differ from medical microscopes in their provision for polarizing the incident light by a more or less fixed and permanent polarizer in the substage, and for analyzing the transmitted light by means of a second polarizing element called the analyzer, which is mounted in a slide so as to be easily moved into or out of the optical path. An accessory slot at 45° to the vibration planes of the polarizer and analyzer is usually located in the body tube below the analyzer. The arrangement of fixed polarizer and movable analyzer is not the only possible scheme that permits examination of mineral grains both in plane polarized light and with crossed nicols. An alternative arrangement is a fixed analyzer in the body tube, and a removable polarizer in the substage. This arrangement is very easily added to certain student microscopes made by the Bausch and Lomb Optical Company and by the American Optical (Spencer Lens) Company, since both manufacturers provide a rotatable disc carrying several holes to control the aperture in the substage. If a diffusing screen of ground glass is present close to the plane of the stage to give illumination of large numerical aperture, it must be relocated below the polarizer.

In the Spencer No. 78 microscope, a heat-reflecting metal stop is located immediately above the built-in lamp in the substage. The instrument is purchased without the standard blue ground glass disc in the stage, and a ground glass must be cemented to the top of the heat-reflecting stop immediately above the lamp. Duco cement has proved satisfactory in the first few months' use of one of these instruments. Polaroid film is cemented over the largest and second-smallest holes in the aperture-control disc, in such an orientation that the vibration-direction is east-west, to correspond to that of the removable element (analyzer) of the conventional petrographic microscope. This can be done accurately with the aid of a conventional petrographic microscope provided with a crosshair eyepiece, as follows: the aperture disc is removed and a line is scratched on it to indicate the direction between the center of the disc and the center of each hole that is to be covered with polaroid. The disc is then placed on the stage of the regular polarizing microscope, and using the lowest magnification, this line is made exactly parallel to the north-south crosshair. A square of polaroid film is then laid over the hole and cemented in place in such an orientation that it appears completely dark when viewed in plane-polarized light. Minor adjustments to its orientation can be made just before the cement hardens.

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[1] Presented orally before the annual meeting of the Crystallographic Society of America at Ann Arbor, April 9, 1949.

The analyzer may be installed permanently in the tube, or in the ocular. It is more easily placed and adjusted in the ocular, but then interference figures can only be seen by using a hand lens (6× to 10×) to examine the image projected in the Ramsden disc about 5 mm. above the eyepiece, according to Klein's method.[2]

To permit the use of Lasaulx' method[3] which requires simply the removal of the ocular, the analyzer must be installed in the tube of the microscope. In the Spencer No. 78 microscope, the lower end of the short tube that receives the eye-piece is accessible for this purpose. This tube may be unscrewed from the top of the body tube. A round polaroid disc is inserted against a shoulder in the bottom of the tube, and held in place by a narrow strip of string brass, bent to form a ring. Adjustment of this polaroid to crossed position must be done by turning it in its mount with the point of a sharp needle after reassembling the tube to the microscope. Cement can be applied to make this adjustment permanent, if desired.

Rotating Stage

Figure 1 is a working drawing of the rotating stage made in a University machine shop. It is turned from brass stock $\frac{1}{8}$ inch thick. The edge may be knurled as indicated, or not. The bearing for this stage is made from thinner stock and fitted to the sleeve-bearing carefully so as to have the minimum lateral play consistent with easy turning. It is drilled and tapped for screws *considerably smaller* than the holes provided by the manufacturer for stage clips; the axis of rotation is centered for the highest power objective just before the screws are finally tightened. The hole in the stage of the microscope was originally to be the bearing, but it is too far from the optical axis of the microscope to permit work with the medium-high power (8-mm., 20×) objective. Trial showed that the ground glass is too far from the surface of the rotating stage to cover the angular aperture of the commoner high-power (4-mm., 45×)[4] objec-

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[2] Johannsen, Manual of Petrographic Methods, 1918, p. 450.

[3] *Ibid.*, p. 449.

[4] The 4-mm., 44× objective with N.A. = 0.66 is satisfactory, however, and can be recommended although its higher magnification requires appreciably more care in the fabrication of the bearing for the rotating stage.

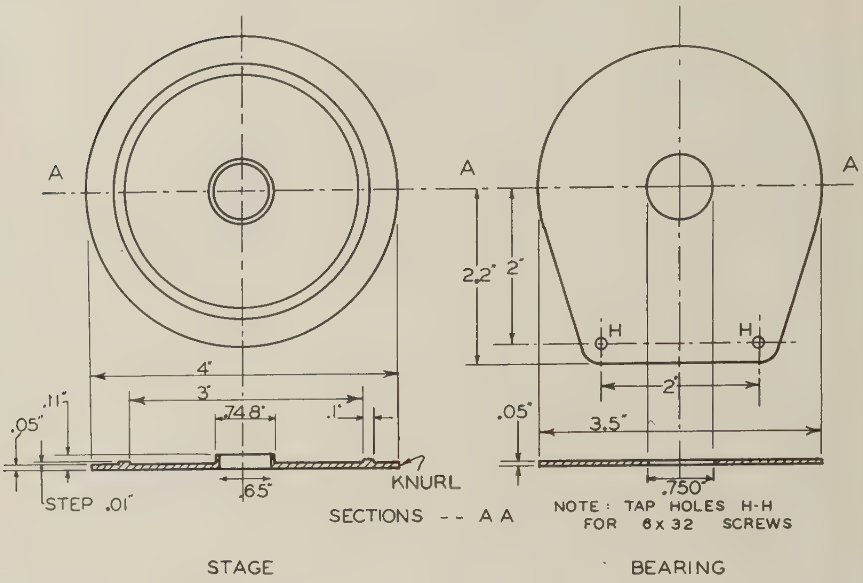

Fig. 1

tive, and there seems to be no convenient way to bring it nearer the objective while still keeping it below the removable polarizer.

Accessory Slot

The manufacturer offered to provide an accessory slot above the objective-changer at nominal cost, and if all accessory plates are to be used, this offer would be accepted. It may be pointed out that such a slot is not an absolute necessity. Quarter-wave and first-order-red plates may be made by splitting a piece of muscovite, or indeed by mounting a piece (or pieces) of cellophane between thin glass plates. These accessories may be used either in the slot or below the medium-power objective, or one of them may be mounted permanently with a polaroid over one of the holes in the aperture-control disc. The cost of a standard quartz wedge and other accessories is comparable to that of the whole microscope, and can be avoided by the above expedient.

Discussion

Trial showed that strain-free objectives are necessary for satisfactory production of interference figures. Choosing thin grains with high interference colors to obtain Nx and Nz, and thick grains with low interference colors for No and Ny, the use of interference figures is not absolutely necessary for index determinations by the powder immersion method.

Accessory slot and plates may then be dispensed with. Specifying 8-mm., 20×, 0.50 N.A. and 25-mm., 5.1×, 0.17 N.A. strainfree objectives, in a double revolving nosepiece, and 10× ocular as equipment, making the rotating stage and bearing according to the figure, and installing polaroid film polarizer and analyzer ourselves, the cost of six of these microscopes has been kept below $120.00 each.

An alternative to having one polarizing element completely removable is to have it rotatable from crossed to parallel position. After turning a mineral grain to extinction with the movable element in crossed position, it would be rotated to the parallel position, enabling refractive index observations to be made on one transmitted ray at a time. An annoying feature of this arrangement is the interference colors developed in mineral grains that are not at the "extinction" position.

This microscope is advertised by the manufacturer as of particularly rugged construction, to withstand the use and abuse of students at almost any level. Ruggedness naturally contributes to its usefulness for instruction at the lowest level of elementary courses in mineralogy and chemistry. Modern trends in mineralogy demand such instruction at the earliest possible stage, and student interest in the use of microscopic methods is immediate. Superior ruggedness and low price also open up possibilities of entirely new uses. These characteristics permit the direct introduction of microscopic work with geologic field studies. Most field geologists would hesitate to take a regular petrographic microscope with them for a summer's field work, even though they would find many uses for it in evenings and on rainy days, if it were available. They would not hesitate to take a rugged microscope that costs little more than a good camera or other indispensable field equipment. This microscope might encourage application of optical methods by advanced amateurs, perhaps through cooperation of museums and mineral clubs. Other special uses for this polarizing microscope do not need to be listed for readers of this Journal. There is plainly a wide application for such equipment if it proves as practical in years of use as the first model has already proved in months.

WOLFEITE, XANTHOXENITE, AND WHITLOCKITE FROM THE PALERMO MINE, NEW HAMPSHIRE*

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ABSTRACT

Wolfeite, a new species, has the composition $(Fe'', Mn'')_2(PO_4)(OH)$ and occurs as a hydrothermal alteration product of triphylite at the Palermo pegmatite, North Groton, New Hampshire. Monoclinic prismatic, with $a_0 = 12.20$ Å, $b_0 = 13.17$, $c_0 = 9.79$; $\beta = 108°$; $Z = 16$. Cleavage {100} good, {120} fair, {010} poor, {110} very poor. Specific gravity 3.79. Optically biaxial positive, with $nX = 1.741$, $nY = 1.742$, $nZ = 1.746$; $r > v$ very strong; 2V medium. Analysis gave: CaO 0.19, MgO 2.28, MnO 13.12, FeO 44.44, Fe_2O_3 0.70, P_2O_5 32.90, H_2O 3.78, F 0.51, Na_2O 0.14, K_2O 0.05, Li_2O 0.56, insol. 1.44; total 100.11. Wolfeite is isostructural with triploidite $(Mn'', Fe'')_2(PO_4)(OH)$, and sarkinite $Mn''_2(AsO_4)(OH)$, and forms an isomorphous series with triploidite extending from Fe:Mn = 1:3.30 to Fe:Mn = 3.39:1 at least, and probably to the pure iron end member. The name wolfeite is applied to that part of the triploidite-wolfeite series with Fe > Mn. Wolfeite also occurs at Cyrillhof, Moravia, at Skrumptetorp, Sweden, and at Hagendorf, Bavaria.

Xanthoxenite, hitherto known only from Rabenstein, Bavaria, on the basis of a partial description, occurs abundantly at the Palermo mine. Composition: $Ca_2Fe'''(PO_4)_2(OH) \cdot 1\frac{1}{2}H_2O$ from the analysis: CaO 24.99, MgO 0.91, MnO 4.55, Fe_2O_3 21.68, Al_2O_3 0.01, P_2O_5 37.62, H_2O+ 9.13, H_2O- 0.86, insol. 0.78; total 100.53. As crusts or masses of indistinct platy or lath-like crystals. Monoclinic or triclinic. One perfect cleavage. Hardness $2\frac{1}{2}$. Specific gravity 2.97. Color pale yellow to brownish yellow. Optically biaxial negative with $nX = 1.704$, $nY = 1.715$, $nZ = 1.724$; 2V large, $r < v$ strong.

Whitlockite crystals from a new find at Palermo gave on analysis: CaO 46.84, MgO 1.91, FeO 2.34, MnO 0.76, Fe_2O_3 0.20, Al_2O_3 0.11, P_2O_5 45.94, Cl 0.03, F 0.07, H_2O 0.66, CO_2 0.14, Na_2O 0.59, K_2O 0.01, insol. 0.34; total 99.94. Specific gravity 3.09. The analysis confirms the accepted formula, $(Ca, Mg, Fe)_3(PO_4)_2$. The new forms $j\{20\bar{2}3\}$, $k\{1.0.\bar{1}.10\}$, $g\{01\bar{1}3\}$ and $h\{01\bar{1}8\}$ are noted, and a new habit tabular on {0001} is described.

Roscherite, hitherto known only from Ehrenfriedersdorf, Saxony, is noted from two new localities: the Nevel mine, Newry, Maine, and Black Mountain, Rumford, Maine. The mineral occurs as fibrous botryoidal masses with albite in pegmatite.

WOLFEITE

Early in 1947, several huge triphylite crystals were encountered during mining operations for feldspar and beryl in the Palermo pegmatite at North Groton, New Hampshire. A cleavage mass of the mineral weighing about 1000 pounds was thrown on the dump heap of the quarry at that time, where it has been broken down and largely removed by mineral collectors during the course of the past two years. The triphylite, which was of a bluish gray color on fresh surfaces, locally contained irregular grains up to an inch or so in size of a reddish-brown cleavable mineral. This mineral was first noticed by Professor C. W. Wolfe of Boston University and was tentatively identified by him as triploidite. The mineral is a hydrothermal replacement of the triphylite and is associated with

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* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 306.

indistinct veinlets containing chlorite, sphalerite, pyrite and arsenopyrite. Several months later further operations in the quarry exposed another large triphylite crystal that had been partly reworked hydrothermally into a granular aggregate composed of residual triphylite, siderite, quartz, apatite, plagioclase, ludlamite and abundant columnar-fibrous masses of a dark clove-brown mineral. The latter mineral was found by the writer to afford an *x*-ray powder pattern identical with that of triploidite, but with smaller cell dimensions, and the indices of refraction proved to be considerably higher than those of the Branchville triploidite. These facts, together with the occurrence of the mineral as an alteration product of triphylite, rather than of lithiophilite as at Branchville, suggested that the material was the iron analogue of triploidite. A satisfactory analysis sample could not be obtained from this material by any reasonable effort due to admixture. An examination of the reddish-brown granular mineral mentioned above, however, proved it to be identical with the dark clove-brown mineral at hand, although with slightly lower indices of refraction, and an analysis sample was obtained therefrom without difficulty. The analysis, cited in Column 7 of Table 1, proves that the mineral is in fact the iron analogue of triploidite.

TABLE 1. CHEMICAL ANALYSES OF TRIPLOIDITE-WOLFEITE

	1	2	3	4	5	6	7	8
CaO		0.33	(∼0.90)	0.56	2.00	1.27	0.19	
MgO				4.74		0.40	2.28	
MnO	63.95	48.45	43.46	29.85	21.73	17.92	13.12	
FeO		14.88	18.87	24.31	36.44	33.37	44.44	64.24
Fe_2O_3				4.26	0.22	7.78	0.70	
P_2O_5	31.99	32.11	32.62	30.89	34.20	32.44	32.90	31.73
H_2O	4.06	4.08	4.14	4.20	4.50	4.48	3.78	4.03
F		none		tr.	0.09	0.88	0.51	
Rem.			1.09	0.94	1.27	2.47	2.19	
Total	100.00	99.85	100.18	99.75	100.45	101.01	100.11	100.00
G		3.697			3.78		3.79	
Fe:Mn		1:3.30	1:2.39	1:1.07	1.66:1	2.22:1	3.39:1	

1. Theoretical composition, $Mn_2''(PO_4)(OH)$. 2. Triploidite, Branchville. Brush and Dana (1878). 3. Triploidite, Branchville. Rem. is quartz, CaO estimated. Brush and Dana (1878). 4. Triploidite, Wien, Moravia. Herles analysis in Kovář and Slavík (1900). Fe_2O_3 due to oxidation of FeO and calculated as such in the Fe:Mn ratio. 5. Wolfeite, Skrumptetorp, Sweden. Rem. is Na_2O 0.93, K_2O tr., H_2O- 0.19, insol. 0.15. Berggren analysis in Mason (1941). 6. Wolfeite, Cryillhof, Moravia. Rem. is $(Na, K)_2O$ 0.17, insol. 2.30. Herles analysis in Kovář and Slavík (1900). Fe_2O_3 due to oxidation of FeO and calculated as such in the Fe:Mn ratio. 7. Wolfeite, Palermo, N. H. Peck analysis, 1948. Rem. is Na_2O 0.14, K_2O 0.05, Li_2O 0.56, insol. 1.44. 8. Theoretical composition, $Fe_2''(PO_4)(OH)$.

The derived formula is $(Fe, Mn, Mg)_2(PO_4)(OH)$, with $Fe'':Mn'':Mg = 11.1:3.27:1$. A partial analysis of the triphylite from which the mineral was derived gave FeO 38.81 and MnO 8.25 per cent, or $Fe:Mn = 4.65:1$. The name wolfeite is proposed for the mineral and is particularly appropriate in view of Professor Wolfe's studies of iron and manganese phosphates from Palermo and other localities. Wolfeite is isostructural with triploidite and forms an isomorphous series with that mineral extending over the range $Fe:Mn = 1:3.30$ to $Fe:Mn = 3.39:1$ at least. The name wolfeite is properly applied to that part of the series with $Fe > Mn$ in atomic per cent.

Morphology and Structure Cell. Euhedral crystals of wolfeite have not been found at Palermo. The mineral occurs either massive granular, or as slender columnar or coarse fibrous aggregates elongated [001] and ranging up to an inch or so in length. The columnar material sometimes shows a few crystal faces where it contacts quartz, and the forms {120} and {100} were identified. In the following section, it is shown that an unanalyzed mineral from Hagendorf, Bavaria, earlier described as triploidite, actually has $Fe > Mn$ and hence is properly classed as wolfeite. This mineral was described morphologically by Müllbauer. His elements and forms are given in Table 2 in comparison with those of E. S. Dana obtained on Branchville triploidite with $Fe:Mn = 1:3.30$. The elements of these workers are here given with the b-axis doubled to conform with the structure cell determined by Kokkoros on the Hagendorf material

Table 2. Angle Table for Triploidite-Wolfeite

Monoclinic; prismatic $-2/m$

$a:b:c = 0.9258:1:0.7442$; $\beta = 108°18'$ (for Hagendorf wolfeite crystals with $Fe:Mn > 3:1$).
$a:b:c = 0.9286:1:0.7463$; $\beta = 108°14'$; $p_0:q_0:r_0 = 0.8037:0.7088:1$; $r_2:p_2:q_2 = 1.4108:1.1338:1$; $\mu = 71°46'$; $p_0' = 0.8462$; $q_0' = 0.7463$; $x_0' = 0.3294$ (for Branchville triploidite crystals with $Fe:Mn = 1:3.30$ (?)).

Forms	Branchville triploidite	Hagendorf wolfeite	ϕ	ρ	ϕ_2	$\rho_2 = B$	C	A
c 001	*	*	90°00′	18°14′	71°46′	90°00′	—	71°46′
b 010	*	*	0 00	90 00	—	0 00	90 00	90 00
a 100	*	*	90 00	90 00	0 00	90 00	71 46	0 00
n 120	*	*	29 33	90 00	0 00	29 33	81 07	60 27
m 110		*	48 35	90 00	0 00	48 35	76 26	13 34
e 021	*	*	12 26	56 48	71 46	35 12	54 48	79 36
ρ 203		*	90 00	41 47	48 13	90 00	23 33	48 13
p $\bar{2}21$	*		−42 24	63 40	143 44	48 33	76 35	127 11

and verified by Richmond on the Branchville material and by the writer on the Palermo material. An angle table for the known forms of triploidite-wolfeite based on Dana's elements for the Branchville crystals is also given in Table 2.

The unit cell dimensions found for material in the triploidite-wolfeite series are listed in Table 3. The *x*-ray powder spacings are given in Table 4. The space group is $P2_1/a$.

TABLE 3. UNIT CELL DIMENSIONS OF TRIPLOIDITE-WOLFEITE

Locality	Triploidite Branchville (Richmond)	Wolfeite Palermo (Frondel)	Wolfeite Hagendorf (Kokkoros)
Fe:Mn	1:3.30(?)	3.39:1	>3:1
a_0	12.26 Å	12.20 Å	12.12 Å
b_0	13.38	13.17	13.16
c_0	9.90	9.79	9.73
β	108°4′	108°	108°18′
$a_0:b_0:c_0$	0.916:1:0.740	0.926:1:0.743	0.921:1:0.739

TABLE 4. *X*-RAY POWDER SPACING DATA FOR TRIPLOIDITE-WOLFEITE

Iron radiation ($\lambda=1.937$), *manganese filter. Some faint lines have been omitted, and no lines are given below 1.70.*

Triploidite Fe:Mn 1:3.30(?)		Wolfeite Fe:Mn 3.39:1
I	*d*	*d*
3	4.40	4.37
4	3.65	3.63
5	3.41	3.37
8	3.19	3.18
9	3.10	3.09
10	2.94	2.93
1	2.89	2.87
4	2.84	2.80
1	2.71	2.69
1	2.65	2.63
5	2.58	2.57
3	2.47	2.45
1	2.35	2.33
5	2.31	2.29
1	2.19	2.19
5	2.15	2.14
1	2.06	2.06
1	2.05	2.04
1	2.01	2.01
3	1.98	1.96
3	1.95	1.95
1	1.83	1.82
6	1.80	1.79
1	1.76	1.75
2	1.72	1.71

Physical Properties. The hardness of wolfeite is 4½ to 5. The specific gravity of the reddish-brown analyzed material from Palermo is 3.79;

the variation in specific gravity with Fe:Mn ratio is shown in Fig. 1. The luster is vitreous but in columnar-fibrous types tends toward silky. The color varies in shades from reddish-brown to dark clove-brown and in general is similar to but darker than triploidite. Small grains are transparent.

Wolfeite from Palermo has four different cleavage directions in a single zone, [100], and probably is unique in this regard. A columnar cleavage fragment when measured goniometrically was found to give no less than 12 reflections from cleavage surfaces, corresponding to the forms {010}, {100}, {120} and {110}. Confirmatory measurements were obtained on a number of fragments, although not all of the equivalent cleavage directions were present on each. Optical and Weissenberg *x*-ray study of several such fragments gave no evidence of twinning or intergrowth. The quality of the cleavages is as follows: {100} good, {120} fair but interrupted, {010} poor and interrupted, {110} very poor and interrupted. Only the {100} cleavage has hitherto been reported; fragments of the Branchville triploidite, however, were found to show cleavage on {120} and {010} in addition to {100}. The fracture of wolfeite-triploidite is uneven to subconchoidal.

The indices of refraction of the granular and columnar types of wolfeite from Palermo are given in Table 5, together with Larsen's data on the Branchville triploidite (here verified) and new data on the Hagendorf material. The indices increase with increase in the Fe:Mn ratio as shown in Fig. 1. The graph is not entirely satisfactory since the data on the Branchville mineral was not obtained on an analyzed sample and it is known that the material from this locality, as at Palermo, varies somewhat in composition (see analyses 2 and 3 in Table 1). Further the linear variation assumed may not be correct, especially since the effect of the small amount of Ca and Mg present in subsitution for (Fe, Mn) is not known.

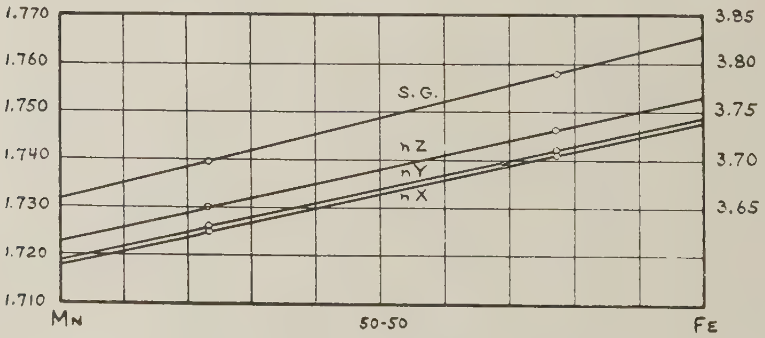


FIG. 1. Indices of refraction and specific gravity of the triploidite-wolfeite series.

Wolfeite from Other Localities. Material termed triploidite has been described from five localities, but several of these minerals have Fe > Mn and are properly classed as wolfeite. The original triploidite described by Brush and Dana from Branchville varies slightly in composition, with Fe:Mn = 1:3.30 and Fe:Mn = 1:2.39 in the two reported analyses (Table 1). The actual composition of the Branchville material studied optically by Larsen and used by Richmond in his *x*-ray study is not known; the data of Fig. 1 are plotted for a Fe:Mn ratio of 1:3.30 corresponding to the lighter colored, more common, material. The triploidite from Wien, Moravia, analyzed by Kovář and Slavík has Fe:Mn = 1:1.07 and hence is true triploidite. On the other hand, the mineral from Cyrillhof, Moravia, described by these writers has Fe:Mn = 2.22:1 and hence properly is wolfeite. Optical and *x*-ray data are lacking for the material of these two occurrences. It is not certain if the material from Cyrillhof, at least, actually belongs in the wolfeite-triploidite structure type and it may be an altered form of graftonite as suggested by Mason. The so-called triploidite from Skrumptetorp, Sweden, described by Mason also is wolfeite since it has Fe:Mn = 1.66:1. The indices of refraction given by Mason for this material ($n\mathrm{X} = 1.725$, $n\mathrm{Z} = 1.731$) are much too low for the composition and are believed to be in error. Finally, so-called triploidite also has been described by Müllbauer from Hagendorf, Bavaria. A chemical analysis of this material is lacking. The indices of refraction, however, correspond virtually to the pure iron compound according to the data of Fig. 1 and Table 5. The specific gravity, 3.78, and the unit cell dimensions (Table 3) also indicate a high-iron compound but these data probably contain relatively large errors and do not give a consistent Fe:Mn ratio.

TABLE 5. OPTICAL DATA FOR THE TRIPLOIDITE-WOLFEITE SERIES

Locality	Triploidite Branchville	Wolfeite Palermo (granular)	Wolfeite Palermo (fibrous)	Wolfeite Hagendorf
Fe:Mn	1:3.30(?)	3.39:1		>3:1
nX	1.725	1.741	1.747	1.748
nY	1.726	1.742	1.748	1.749
nZ	1.730	1.746	1.752	1.753
$\mathrm{Z} \wedge c$	−4°		−31°	

Dispersion $r > v$, very strong. 2V medium. Faintly pleochroic in very thick grains, with absorption Z > X, Y.

Chemistry. A complete series extends between triploidite and wolfeite from Fe:Mn = 1:3.30 (analysis 2) to Fe:Mn = 3.39:1 (analysis 7) at least. The series probably extends up to the nearly pure iron end member according to the optical data on the Hagendorf material. Both Ca and Mg substitute in small amounts for (Fe, Mn), with Ca:(Fe, Mn) = 1:22.9 in analysis 5 and with Mg:(Fe, Mn) = 1:6.92 in analysis 4. The composition of triploidite-wolfeite differs from that of triplite only in the presence of F in place of (OH). These species have in fact been earlier thought to be isostructural and isomorphous on the basis of this similarity in formula. *X*-ray powder diffraction study by the writer and by Mason and the single-crystal *x*-ray study of triplite by Heinrich and Wolfe indicates however, that these species are distinct. F apparently can substitute in small amounts for (OH) in the triploidite-wolfeite structure, with F:(OH) = 1:5.37 in analysis 6; it is possible that part of the F in this particular analysis is due to admixed triplite. It may also be noted that considerable amounts of Fe_2O_3 have been reported in triploidite-wolfeite. The largest amounts occur in more or less altered material from Wien and Cyrillhof in Moravia (analyses 4 and 6) and is due to partial oxidation of original Fe″ to Fe″′. Triploidite-wolfeite is isostructural with sarkinite, $Mn_2(AsO_4)(OH)$, as shown by Hägele, but there is no evidence for an isomorphous series between these minerals.

XANTHOXENITE

Xanthoxenite occurs abundantly although inconspicuously at the Palermo mine as one of the last formed of the hydrothermal reworked products of triphylite. Open cavities in the triphylite crystals are variously lined with crystals of quartz, siderite, apatite, whitlockite, childrenite-eosphorite, amblygonite and other phosphates formed during the later stages of hydrothermal mineralization and it is upon these minerals that the xanthoxenite is deposited.

Physical Properties. Xanthoxenite occurs as crusts and masses composed of indistinct platy or lath-like crystals often aggregated in lamellar fashion. The hardness is about 2½ and the specific gravity is about 2.97; both values probably are somewhat in error because of the physical nature of the material. The color of the mineral is pale yellow to brownish yellow, and the luster is dull to slightly waxy. Under the microscope, xanthoxenite is pale yellow to slightly lemon yellow in color. Very thick grains are faintly pleochroic in yellow with absorption $Y > X, Z$. For the most part the mineral appears as shreds and flakes with a perfect cleavage but without definite outline. Occasionally lozenge-shaped grains are observed. These apparently are cleavage sections through crystals, and their optical orientation and plane angles are shown in Fig. 2. On edge the flakes show inclined extinction with Y′ making a maximum angle with the elongation of about 43°. The mineral is either monoclinic with

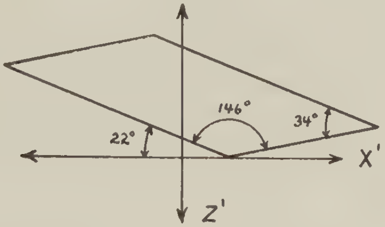


FIG. 2. Optical orientation of xanthoxenite.

the cleavage in the zone [010] or is triclinic. Dispersion is strong and some orientations show the ultra-blue. The optical properties are given below.

nX 1.704 ± 0.003	Optically negative (−)
nY 1.715 ± 0.003	2V large
nZ 1.724 ± 0.003	Dispersion strong, $r<v$

Some variation may be expected in these characters since both Mn and Mg may substitute to some extent for the main cation, Ca. Xanthoxenite differs markedly in optical properties from calcioferrite, its closest neighbor chemically. The latter mineral is uniaxial negative with $O=1.57$, $E=1.575$.

Identity with Xanthoxenite. The mineral at hand was originally thought to be a new species since a search of the literature revealed no known mineral with identical properties. Among the minerals which came under consideration was an ill-defined substance described under the name xanthoxenite by Laubmann and Steinmetz from the Hühnerkobel pegmatite near Rabenstein, Bavaria. This substance occurred as radial aggregates of unmeasurable gypsum-like crystals flattened on {010} with a clinodome making an angle with [001] of about 41° as seen under the microscope. Color wax-yellow to reddish brown. Specific gravity 2.844. Perfect cleavage {010}. Optically; biaxial negative with $Z \wedge c = +36°$ and a birefringence of about 0.05. Pleochroic, with Z bright yellow and Y light yellow. The mineral was said on the basis of qualitative tests to be a hydrated ferric phosphate with considerably smaller amounts of manganese and calcium, and demonstrable amounts of aluminum and magnesium. A partial chemical analysis gave P_2O_5 32.61 per cent and H_2O 16.10 per cent (by ignition). Three specimens labelled xanthoxenite from Hühnerkobel were available in the Harvard collection but these exhibited nothing that answered the description of the mineral. After this work was completed another specimen labelled xanthoxenite from Hühnerkobel fortunately came to hand through the interest of S. G. Gordon of the Philadelphia Academy of Natural Sciences. This specimen showed a small amount of a mineral identical in appearance and properties with the Palermo mineral. No crystals or bounded cleavage flakes were observed. The conclusion thus seems forced that the Palermo mineral is identical with xanthoxenite, in spite of the discrepancies in the description of the two substances. The partial chemical analysis of the Hagendorf material was probably made on a micro-sample and may be considerably in error, and the seeming differences in crystal form and optical orientation may possibly be due to unlike crystal habits. The *x*-ray powder patterns of the two substances are identical. A complete re-examination of the type xanthoxenite from Hagendorf would, however, still be desirable.

An analysis of another mineral perhaps identical with xanthoxenite has been published by Schaller. This substance, labelled "near dufrenite," was found at Grafton, New Hampshire [about 25 miles from the Palermo mine]. The analysis affords ratios near those of xanthoxenite and mitridatite but closer to the suggested formula for the latter substance. Descriptive details are lacking, and it is impossible to obtain such data since the only known specimen has been lost.*

Composition and Systematic Relations of Xanthoxenite. A chemical analysis, cited in Table 6, proves xanthoxenite to be a hydrated basic phosphate of calcium and ferric iron with the formula $Ca_2Fe'''(PO_4)_2(OH) \cdot 1\frac{1}{2}H_2O$. Small amounts of Mn and Mg substitute for Ca, with Mg:Mn:Ca = 1:2.8:19.7 in the reported analysis.

TABLE 6. CHEMICAL ANALYSIS OF XANTHOXENITE

	1	2	3	4	5	6
CaO	30.31	25.22	24.99	.4456		
MgO		0.92	0.91	.0226 } .5324	3.92	4
MnO		4.59	4.55	.0642		
Fe_2O_3	21.58	21.45	21.68	.1359		
Al_2O_3			0.01		1	1
P_2O_5	38.37	38.14	37.62	.2650	1.95	2
H_2O+	9.74	9.68	9.13	.5116	3.76	4
H_2O-			0.86			
Insol.			0.78			
	100.00	100.00	100.53			

1. Theoretical composition, $Ca_2Fe(PO_4)_2(OH) \cdot 1\frac{1}{2}H_2O$. 2. Theoretical composition of $(Ca, Mn, Mg)_2Fe(PO_4)_2(OH) \cdot 1\frac{1}{2}H_2O$ with Ca:Mn:Mg = 19.7:2.84:1. 3. Xanthoxenite, Palermo, N. H., H. J. Hallowell analysis, 1948. 4. Molecular quotients. 5. Oxide ratio. 6. Ideal oxide ratio.

---

* W. T. Schaller, private communication, 1948.

The description of any phosphate of calcium and ferric iron is attended by much uncertainty, since no less than six minerals with this general composition have been already described and named and few of these can be said to be adequately defined. These minerals are listed and briefly described below. The closest relative to xanthoxenite appears to be the relatively well characterized mineral calcioferrite. Both minerals have the same metal: (PO_4):(OH) ratio but in calcioferrite the ratio of Ca:Fe is 1:1 and in xanthoxenite Ca:Fe = 2:1. None of the other calcium iron phosphates listed shows any relation to xanthoxenite insofar as can be inferred from the available data. Their non-identity with xanthoxenite is supported particularly by the analytical evidence which in all cases shows a ratio of Ca:Fe of 1:2 or greater. Unfortunately, *x*-ray powder diffraction data are not available for any of the minerals listed. The powder data for xanthoxenite are given in Table 7.

TABLE 7. *X*-RAY POWDER DIFFRACTION DATA FOR XANTHOXENITE
Iron radiation ($\lambda = 1.937$ Å), *manganese filter.*

I	*d*	*I*	*d*	*I*	*d*
5	6.24	2	2.68	1	1.84
4	4.94	4	2.60	2	1.72
7	3.48	2	2.46	1	1.65
8	3.22	1	2.36	1	1.57
2	3.12	2	2.30	3	1.53
10	3.05	6	2.23	1	1.44
1	2.96	1	2.08	1	1.41
9	2.73	1	2.01	1	1.36
				1	1.30

Borickite. $CaFe'''_5(PO_4)_2(OH)_{11} \cdot 3H_2O$ (?). Compact reniform masses, in part opaline, with weak waxy luster. Color reddish brown. Isotropic, due to aggregate polarization, with a variable mean index of refraction, 1.57 to 1.67. In part as fibers with high birefringence. Efforts to obtain an *x*-ray powder pattern were unsuccessful. The name was originally applied by Bořicky (1867) and von Hauer (1854) to material with the composition cited from Nenačovic, Bohemia, and Leoben, Austria. The mineral was later classed by some authors with type foucherite and delvauxite and various chemically similar substances ascribed thereto.

Calcioferrite. $Ca_3Fe'''_3(PO_4)_4(OH)_3 \cdot 8H_2O$ (?). Found as foliated, nodular or reniform masses. Color sulfur-yellow to greenish yellow and yellowish white. Perhaps hexagonal in crystallization, with a perfect cleavage parallel to the foliation, another at right angles to this and traces of a third cleavage oblique to the same. H = 2½. G = 2.53. Optically uniaxial negative, with $O = 1.575$ and $E = 1.570$ (Larsen and Berman, 1934). Originally described by Blum (1858) from a Tertiary clay bed at Battenberg, Rhenish Prussia, *x*-ray data are lacking.

Egueite. $CaFe'''_{14}(PO_4)_{10}(OH)_{14} \cdot 21H_2O$ (?). Described by Garde (1909) and Lacroix (1910) as occurring as fibrous-lamellar nodules in clay impregnated with trona and thenardite in the Eguéï region of Chad Territory in the Sudan. Friable. Luster vitreous to slightly greasy. Apparently monoclinic, but isotropic due to aggregate polarization with a mean index of refraction of 1.65 (Larsen, 1921). Brownish yellow in color, with G=2.60. *X*-ray data are lacking.

Foucherite. $Ca(Fe,Al)_4(PO_4)_2(OH)_8 \cdot 7H_2O$ (?). Compact, brownish red globules. H=3½. G=2.7. Found in sandstone at Fouchères, Champagne, France (see Lacroix, 1910). *X*-ray and optical data are lacking. Colloform minerals from Litošice (n=1.648) and St. Benigna, Bohemia, described by Ulrich (1922) and Slavík (1918) have been ascribed to this ill-defined species. Foucherite may be identical with borickite.

Mitridatite. $CaFe'''_2(PO_4)_2(OH)_2 \cdot nH_2O$ (?). A name given to various ill-defined metacolloidal substances found in oolitic iron ores on the Kerch and Taman peninsulas, southern Russia. Massive, as nodules, crusts and veinlets. Structure earthy and pulverulent or friable to dense and gum-like. Color greenish yellow to dark green; also brownish green to yellowish brown and brownish black. Luster earthy to resinous. Isotropic. Optical and *x*-ray data are lacking. Ten analyses have been reported (see Popoff, 1910; Chukhrov, 1937; Sidorenko, 1945). It is not certain if these analyses represent one or several different minerals, and some apparently were made on mixtures. A few analyses approach the formula cited.

Richellite. $Ca_3Fe'''_{10}(PO_4)_8(OH)_{12} \cdot nH_2O$ (?). Compact or foliated masses and radially fibrous globules. H=2−3.G∼2. Color reddish to yellowish brown. Luster greasy to horn-like. Described by Desprets and Cesàro (1883) from Richelle near Visé, Belgium, associated with halloysite, allophane and koninckite. Optical and *x*-ray data are lacking.

The only other hydrated basic phosphate of divalent and trivalent cations of the same formula type as xanthoxenite is the little-known mineral roscherite:

xanthoxenite	$Ca_2Fe'''(PO_4)_2(OH) \cdot 1\frac{1}{2}H_2O$
roscherite	$(Mn, Fe, Ca)_2Al(PO_4)_2(OH) \cdot 2H_2O$

An authentic specimen of roscherite from Ehrenfriedersdorf, Saxony, the type locality, showed no similarities in optical characters or *x*-ray powder pattern to xanthoxenite. Two new localities for roscherite were found in the course of this work, at the Nevel mine, Newry, Maine, and at Black Mountain, Maine. At both localities the mineral occurs as fibrous botryoidal aggregates associated with albite in pegmatite. Roscherite probably has been mistaken at other pegmatite localities for the fibrous types of eosphorite-childrenite, which it greatly resembles.

WHITLOCKITE

Whitlockite, identical with the beta polymorph of $Ca_3(PO_4)_2$ known from slag systems, was first found (8) in nature at the Palermo mine in 1941. The species was later described as a minor constituent of phosphate-rock from four localities in the West Indies (9), as a cave-deposit at Sebdou, Algeria (1), and as a constituent of urinary calculi and pathological concretions in the human body (10). Whitlockite occurs abundantly although only locally at Palermo, both as granular masses and as euhedral crystals in altered triphylite. The associated minerals include siderite, quartz, apatite, ludlamite, brazilianite, amblygonite, xanthoxenite, childrenite-eosphorite, plagioclase. Wolfeite sometimes occurs in the triphylite as well, but is formed in a very early stage of the hydrothermal alteration as a replacement of that species and is not a crevice or cavity deposit as are the above mentioned minerals. In the original description of whitlockite mention was made of rhodochrosite and of an altered zeolite as associated minerals. The supposed rhodochrosite, based on the occurrence of iron and manganese oxide pseudomorphs after a scalenohedral mineral, has since been found to be siderite or a manganoan variety thereof, and the zeolite apparently is an altered fibrous iron phosphate.

Some newly found whitlockite comprised transparent water-clear crystals and afforded material for both a new chemical analysis and for morphological study. The analysis is cited in Table 8 in comparison with the original analysis on slightly weathered crystals from Palermo and with the material from Algeria. The new analysis confirms the original formula, $Ca_3(PO_4)_2$, and also indicates that the ferric iron reported in the first analysis is due to partial oxidation of ferrous iron present in substitution for calcium. The analysis affords Mn : Fe : Mg : Ca = 1 : 3.2 : 4.4 : 78, the small amount of Fe_2O_3 present being converted into FeO for the purpose

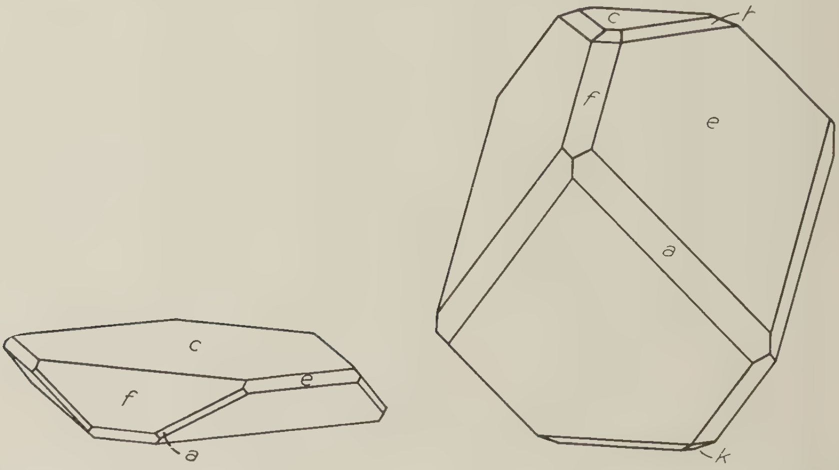
TABLE 8. CHEMICAL ANALYSES OF WHITLOCKITE

	1	2	3	4
CaO	54.22	46.84	46.90	48.15
MgO		1.90	2.53	3.53
FeO		2.34	1.91	
MnO		0.76		0.01
Fe_2O_3		0.20	1.73	0.05
Al_2O_3		0.11		0.06
P_2O_5	45.78	45.94	45.68	45.87
Cl		0.03	tr.	
F		0.07	0.06	
$H_2O\pm$		0.66	0.48	2.00
CO_2		0.14		
Rem.		0.94	0.51	0.04
Total	100.00	99.94	99.80	99.71
G	3.19	3.09	3.12	2.96

1. Theoretical composition, $Ca_3(PO_4)_2$. 2. Whitlockite, Palermo. Peck analysis, 1948. Rem. is Na_2O 0.59, K_2O 0.01, insol. 0.34. 3. Whitlockite, Palermo, Gonyer analysis in Frondel (1941). Rem. is insol. 4. Whitlockite, Sebdou, Algeria. Bennett analysis in Bannister (1947). Rem. is SiO_2.

of the calculation. It is also interesting to note that a small but significant amount of (CO_3) is present, presumably in substitution for (PO_4). It has already been found (9) that some of the whitlockite from insular phosphate-rock contains relatively large amounts of (CO_3), with an accompanying marked lowering of the indices of refraction, and constitutes a variety of the mineral, carbonate-whitlockite, analogous to carbonate-apatite.

Several well-formed whitlockite crystals also were measured goniometrically. An entirely new habit for the mineral is shown in Fig. 3.



Figs. 3 and 4. Crystal habits of whitlockite.

Crystals of this type are rare and the usual habit is rhombohedral. Four new forms were observed, *g* $\{01\bar{1}3\}$, *h* $\{01\bar{1}8\}$, *j* $\{20\bar{2}3\}$ and *k* $\{1.0.\bar{1}.10\}$, and their measured and calculated angles are given in Table 9. Several of the new forms are shown in Fig. 4. The most important form on whitlockite from the point of view of both relative size and frequency of occurrence is $\{01\bar{1}2\}$; it usually comprises the dominant habit either alone or in combination with other faces. The next most important form is $\{0001\}$; it is ordinarily small in size although present on the majority of crystals and only rarely is it developed to the extent shown in Fig. 3. The third and fourth most common forms, $\{10\bar{1}4\}$ and $\{11\bar{2}0\}$, are comparable in frequency of occurrence; both are present only as small modifying facets.

The writer wishes to acknowledge the assistance of Miss Mary Mrose in instrumental work and computations. Mr. H. A. Ashley, operator of

TABLE 9. NEW FORMS ON WHITLOCKITE

$a:c=1:3.5473$; $\alpha=44°40'$; $p_0:q_0=4.0961:1$; $\lambda=114°33\frac{1}{2}'$

Form	Calculated		Measured		Number of faces
j 20$\bar{2}$3	30°00′	69°53′	30°00′	69°41′	3
k 1.0.$\bar{1}$.10	30 00	22 16½	30 00	22 14	10
g 01$\bar{1}$3	−30 00	53 47	−30 00	53 50	3
h 01$\bar{1}$8	−30 00	27 07	−30 00	27 24	6

the Palermo mine, generously presented to the Harvard collection many of the specimens examined in the course of this study.

REFERENCES

1. Bannister, F. A., *Mineral. Mag.* **28,** 29 (1947).
2. Blum, J. R., *Jb. Min.*, 287 **(1858).**
3. Bořicky, E., *Nat. Zeits. Lotos,* March **(1867).**
4. Brush, G. J., and Dana, E. S., *Am. Jour. Sci.*, **16,** 42 (1878).
5. Cesàro, G., and Desprets, F., *Ann. soc. géol. Belg., Mem.*, **10,** 36, (1883); **11,** 257 (1884).
6. Chukhrov, F. V., *Trans. Lomonossov Inst. Ac. Sci. USSR, ser. min.*, no. **10,** 139 (1937).
7. Dana, E. S., *System of Mineralogy,* 6th ed., 779 **(1892).**
8. Frondel, C., *Am. Mineral.*, **26,** 145 (1941).
9. Frondel, C., *Am. Mineral.*, **28,** 215 (1943).
10. Frondel, C., and Prien, E. L., *Jour. Urology,* **57,** 949 (1947).
11. Garde, G., *C.R.*, **148,** 1618 (1909).
12. Hägele, G., *Zbl. Min.*, 267 **(1938).**
13. von Hauer, F., *Jb. geol. Reichs-Anst. Wien,* **5,** 68 (1854).
14. Kokkoros, P., *Zbl. Min.*, 278 **(1938).**
15. Kovář, F., and Slavík, F., *Verh. geol. Reichs-Anst. Wien.*, **50,** 347 (1900); *Zeit. Kryst.*, **36,** 642 (1902).
16. Lacroix, A., *Minéralogie de la France,* **4,** 535, 536 (1910).
17. Larsen, E. S., *U. S. Geol. Surv., Bull.* **679,** (1921).
18. Larsen, E. S., and Berman, H., *U. S. Geol. Surv., Bull.* **848** (1934).
19. Laubmann, H., and Steinmetz, H., *Zeit. Kryst.*, **55,** 579 (1920).
20. Mason, B., *Geol. För. Förh.*, **62,** 373 (1941); **63,** 119 (1941).
21. Müllbauer, F., *Zeit. Kryst.*, **61,** 318 (1925).
22. Richmond, W. E., *Am. Mineral.*, **25,** 469 (1940).
23. Schaller, W. T., *U. S. Geol. Surv., Bull.* **419,** 303 (1910).
24. Sidorenko, A. V., *C. R. Ac. Sci. URSS,* **48,** 53 (1945).
25. Slavík, F., *Bull. Intern. Acad. Bohème,* **22,** 32 (1918).
26. Ulrich, F., *Rozpravy České Akad.*, **31,** no. 10 (1922).
27. Wolfe, C. W., and Heinrich, E. W., *Am. Mineral.*, **32,** 518 (1947).

CHARTING FIVE AND SIX VARIABLES ON THE BOUNDING TETRAHEDRA OF HYPERTETRAHEDRA*

JOHN B. MERTIE, JR.

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ABSTRACT

Triangles, tetrahedra, and hypertetrahedra may be used as reference frames for charting variables whose sums equal unity. The number of variables that may theoretically be charted equals the number of vertices in the figure.

Hypertetrahedra of *n* dimensions are bounded by vertices, edges, triangular faces, tetrahedra, and hypertetrahedra of *n*-1 and fewer dimensions. Direct geometric charting with regard to hypertetrahedra is impossible, as such figures can not be envisaged or constructed; but the variables may be plotted in groups in relation to the bounding triangles and tetrahedra.

Methods were recently presented by the writer for charting five, six, and seven variables on the bounding faces of hypertetrahedra of four, five, and six dimensions. Methods are now presented for charting five and six variables in relation to the bounding tetrahedra of hypertetrahedra of four and five dimensions. For seven variables, these methods have no advantage over charting on the bounding triangular faces. The plotting of variables in relation to the bounding tetrahedra produces surfaces or space curves, of which contour maps or calibrated plane curves are made. Charts are given for the proper presentation of such figures.

Another method is given for projecting directly the quintets of a hypertetrahedron of four dimensions into relationship with one of its bounding tetrahedra. This results in the production of surface contour maps, which ordinarily are best presented as models, photographs, or perspectives. This method is also generalized into five dimensions, but the results are regarded as impracticable.

Trilinear and quadriplanar coordinates are used in this presentation; and data are given for the use of negative coordinates, and for magnification of scale.

INTRODUCTION

Variables or components, whose sums total 100 per cent, may be charted on the boundaries of hypertetrahedra of *n* dimensions. Such boundaries comprise vertices, edges, triangular faces, tetrahedra, and hypertetrahedra of less than *n* dimensions. The boundaries that are useful in practical charting are the triangular faces and the tetrahedra. In a paper recently published, the writer† showed how the bounding triangu-

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† Mertie, John B., Jr., Charting five, six, and seven variables on hypertetrahedral faces: *Am. Mineral.*, **33**, 324–336 (1948).

lar faces may be utilized in charting five, six, and seven variables. The present paper, which is a continuation and completion of this topic, presents methods for charting five and six variables in reference to the bounding tetrahedra.

Trilinear Coordinates

The graphic utilization of positive trilinear and quadriplanar coordinates is almost universal among research workers in the physical sciences, so that this usage need not be described. The analytic applications of these coordinates are not at all well known, but inasmuch as this topic is not a part of this paper, it will likewise be omitted. Certain graphic applications, however, that are not well known, are worthy of mention.

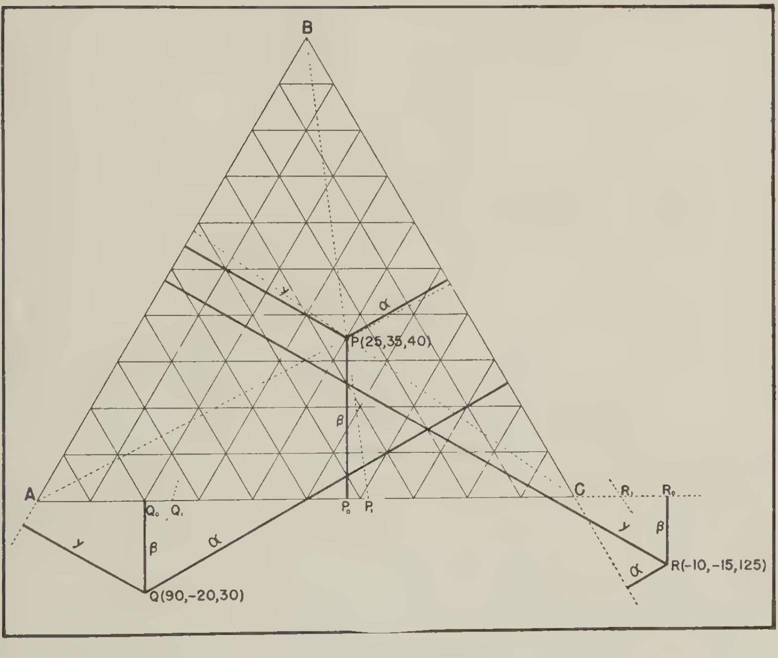

Fig. 1. Positive and negative trilinear coordinates.

An equilateral triangle of reference, *ABC*, known as a trigon, is shown in Fig. 1. A point *P*, having the trilinear coordinates (α, β, γ), or specifically (25, 35, 40), is also shown. Draw the line *BP* and extend it to meet the side *AC*. The intersection, P_1, defines the point that will result from charting the components *A* and *C*, if these are recomputed to 100 per cent. Similar points are indicated, though not lettered, on the sides *AB* and

BC. The point P_0 is the orthogonal projection of P on AC. The bilinear coordinates of P_0 on the line AC are found to be $(\alpha+\beta/2)$, $(\gamma+\beta/2)$, or specifically $(42\frac{1}{2}, 57\frac{1}{2})$. The orthogonal projections of P on the sides AB and BC will define two other points similar to P_0, whose γ and α coordinates are respectively eliminated. This simple projective relationship may be generalized to three and four dimensions.

Negative trilinear coordinates may also be charted. One example of their application was given in the paper cited above, and others might be mentioned. Trilinear coordinates may comprise three positive values, two positive and one negative values, or one positive and two negative values. Three negative coordinates are not possible. A set of coordinates with one negative value will define a point outside the trigon, and opposite the side from which the negative coordinate is measured. A set having two negative coordinates will define a point within the exterior angle formed by extending the sides from which the negative coordinates are measured. Examples in Fig. 1 are the points Q and R, having respectively the coordinates $(90, -20, 30)$ and $(-10, -15, 125)$. The point Q_1 is defined exactly as was the point P_1; and giving due regard to the negative value of β, the point Q_0 becomes the orthogonal projection of Q on the side AC. Using the negative values of α and β, of the point R, the points R_1 and R_0 are similarly located.

QUADRIPLANAR COORDINATES

A regular tetrahedron of reference $ABCD$, with the front face ADC removed, is shown in perspective in Fig. 2. The bounding faces are lined for trilinear coordinates, so that ABC, ABD, and BCD are triangles of reference, or trigons, similar to the one shown in Fig. 1. The point P has the quadriplanar coordinates $(\alpha, \beta, \gamma, \delta)$, or specifically $(15, 20, 30, 35)$. Draw the line DP and extend it to intersect the face ABC. The resulting point, P_1, has the trilinear coordinates that will be obtained by recomputing to 100 per cent the components A, B, and C. The point P_0, which is the orthogonal projection of P onto the side ABC, will be found to have the trilinear coordinates $(\alpha+\delta/3)$, $(\beta+\delta/3)$, $(\gamma+\delta/3)$, or specifically $(26\frac{2}{3}, 31\frac{2}{3}, 41\frac{2}{3})$. Points similar to P_1 and P_0 may be located on each of the other three faces of the tetrahedron, and are in fact shown as unlettered small circles. It is thus feasible to project readily a surface, defined by sets of quadriplanar coordinates, onto any face of a tetrahedron, though ordinarily one such projection will suffice. A line contour map may then be made by drawing curved lines through or between the projected points, at intervals corresponding to selected values of δ, the eliminated coordinate.

Negative quadriplanar coordinates may also be charted, and one example of this application was given in the preceding paper. A set of quadriplanar coordinates may comprise four positive values, three positive and one negative values, two positive and two negative values, or one positive and three negative values. Four negative values are not possible. A set with one negative value will define a point outside the tetrahedron of reference, and opposite the face from which the negative coordinate is measured. A set with two negative values will define a point within the exterior dihedral angle formed by producing the two faces from which the negative coordinates are measured. A set with three negative values will define a point within the exterior trihedral angle formed by producing the three faces from which the negative coordinates are measured. Giving due regard to the negative values of the coordinates, points similar to P_1 and P_0 may be located on all of the bounding faces, or on their extensions beyond the tetrahedron of reference. Surfaces

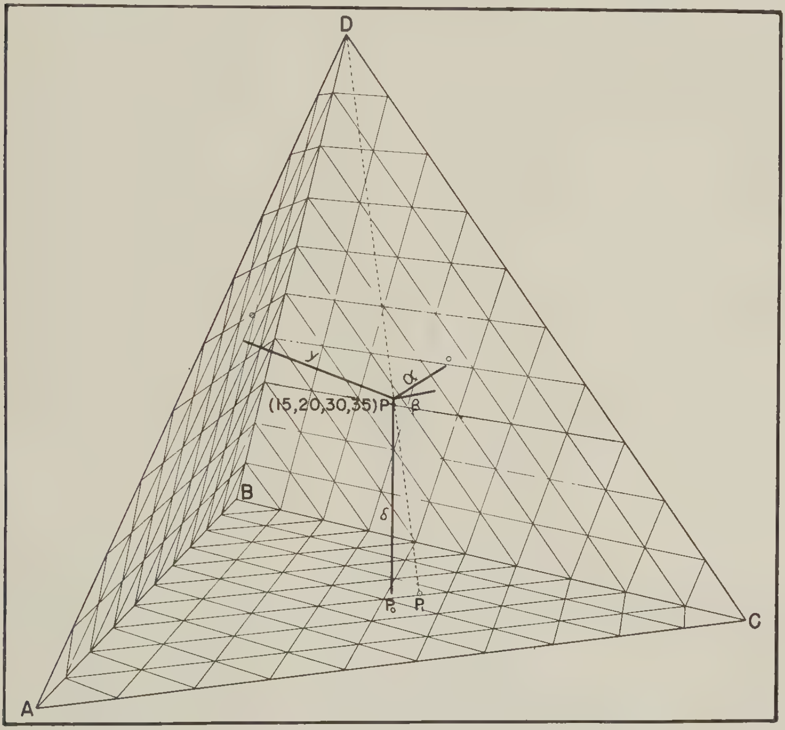

FIG. 2. Quadriplanar coordinates within a tetrahedron.

lying inside or outside the tetrahedron of reference may then be shown as line contour maps, either on the faces of the tetrahedron or on their extensions.

Quartets that are plotted as points in relation to a tetrahedron of reference theoretically define a surface, of which a line contour map may be made. But if such points tend to have a linear disposition, they may be better treated by joining them together as a space curve, and by projecting the space curve orthogonally as a plane curve onto one face of the tetrahedron. The altitudes, or values of the eliminated coordinate, may then be used for calibrating the plane curve, so that it will finally have the appearance of a calibrated curved scale in a nomogram. If some meaning is attached to the sequence of points that lie on the space curve, an arrow may be used on the projected plane curve to indicate this sequence; and if the space curve is numerically related to some physical property, such as grain size, specific gravity, or magnetic susceptibility, the projected plane curve may be doubly calibrated. Thus one calibration will refer to the eliminated coordinate, and the other will give the values of the physical property that is to be shown. Physical properties may similarly be represented on the contour map of a surface, producing thereby a grid pattern. Surfaces and space curves on such surfaces may thus be simultaneously projected, with the result that one or more lines (calibrated or uncalibrated) will intersect the contour lines.

Magnification of Scale

The topic of scale, in plotting triads in relation to trigons, was discussed in the preceding paper.* The methods there given may readily be applied to three dimensions, for plotting quartets in relation to tetrahedra of reference. For magnification of scale, one merely imagines that the tetrahedron is larger than it really is, so sets of coordinates are plotted farther from the vertices of reference than they would normally be. The ratio of the altitude of the imaginary to that of the real tetrahedron of reference is the magnification of scale.

The determining factor in the enlargement of scale is the minimum value of the largest coordinate of a number of sets that are to be charted. Thus if the smallest value of some one coordinate, say α, that exceeds all others in a number of sets, is 50, the maximum amplification of scale is obviously 2. Similarly, if this minimum value of α is 90, the maximum amplification of scale is 10. The same table of possible magnifications that was given in the preceding paper therefore holds for tetrahedra of reference as well as for trigons, as do also the simple formulae earlier given. One statement in the earlier paper, however, needs clarification. On page 333 it was stated that "it is immaterial whether the largest coordinate in the sets is α, β, or γ, *or a mixture of these.*" Insofar as any one trigon is concerned, the italicized clause is incorrect and should be deleted. The clause does apply, however, to different trigons in a composite chart.

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* Mertie, John B., Jr., *Op. cit.*, pp. 332–333.

The magnification of scale in charting triads was shown as a number at the orthocenter of each trigon. For triangles representing the bases of tetrahedra, this central position is preempted by another number that identifies the projected vertex. Some convention must therefore be devised to avoid confusion between these two sets of numbers. It is recommended that the scale factor, both for trigons and for tetrahedra of reference, be placed inside the figure, at the apex that corresponds to the maximum coordinate of the sets. With one exception, the scale number will thus appear in the corners of the triangles. If the largest quadriplanar coordinate of a number of sets, however, is that of the projected apex, the scale number and the apex number must appear together. It is recommended, for this exceptional case, that the scale number be given as a subscript of the apex number, as for example, 5_{20}. These placements of the scale number will serve two purposes: first they will indicate the degree of magnification, and second, they will show the direction of elongation of the imaginary trigon (or tetrahedron of reference).

HYPERTETRAHEDRAL CHARTING

Points that define a surface referred to a tetrahedron may be charted either in multiple on the bounding faces of the tetrahedron, or directly by orthogonal projection onto one of these faces. These methods correspond to plotting four variables, either as four sets of triads defined by points similar to P_1, of Fig. 2; or as one set of points similar to P_0, from which a line contour map may be made. The same alternatives exist in charting points having five coordinates which define a continuum referred to a hypertetrahedron of four dimensions; but the latter is bounded by tetrahedra as well as triangular faces. Therefore, for the hypertetrahedron of four dimensions, three kinds of charting may be done; first, the five variables may be recomputed as triads and charted on or with relation to the bounding triangular faces; second, the five variables may be recomputed as quartets and charted in relation to the bounding tetrahedra; and third, the four-dimensional points may be projected directly into or with relation to a single bounding tetrahedron. The first of these methods was described in the writer's first paper on this subject. The second, which is also a practical method, is described below. The third, though rather difficult and less practicable, is also outlined here.

The most practical methods, either for five or six variables, are to recompute the components as triads and chart them in trilinear coordinates, or to recompute the components as quartets and chart them in quadriplanar coordinates. These two methods require a knowledge of the number of triangles and tetrahedra that bound the various hypertetrahedra. The number and character of these boundaries, though given in the preceding paper, are reproduced again for reference.

BOUNDARIES OF HYPERTETRAHEDRA, FROM FOURTH TO NINTH DIMENSION

	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth
Vertices	5	6	7	8	9	10
Edges	10	15	21	28	36	45
Triangles	10	20	35	56	84	120
Tetrahedra	5	15	35	70	126	210
H_4	1	6	21	56	126	252
H_5	0	1	7	28	84	210
H_6	0	0	1	8	36	120
H_7	0	0	0	1	9	45
H_8	0	0	0	0	1	10
H_9	0	0	0	0	0	1

In this tabulation, H_4, H_5, etc., refer to hypertetrahedra of the fourth, fifth, and higher dimensions.

This tabulation shows that 10 triangles or 5 tetrahedra are required for charting 5 variables; that 20 triangles or 15 tetrahedra are required for charting 6 variables; and that 35 triangles or the same number of tetrahedra are required for charting 7 variables. The charting of quartets referred to a tetrahedron is superior to that of charting triads referred to a trigon, because the relationships between four variables are simultaneously shown, but the former method is more laborious than the latter. For five or six variables, however, the additional labor is to some degree compensated by the fact that fewer tetrahedra than triangles are required. But for seven variables, no such compensation exists, as the number of required tetrahedra and triangles are the same, and charting on the bounding tetrahedra becomes very laborious. Therefore the method of charting quartets in reference to bounding tetrahedra is utilized only in plotting five and six variables.

When five or six variables are recomputed as quartets, and are plotted with reference to bounding tetrahedra, the resulting surfaces may be shown either as three-dimensional models, as photographs or perspective drawings, or as line contour maps. Space curves may be similarly shown, except that one or more calibrated plane curves will result instead of a line contour map. The method of line contour mapping and of space curve projection is here utilized. Five tetrahedra are required to chart the five variables, and therefore one face of each tetrahedron needs to be reproduced in order to show five contour maps or plane curves. This requires a compact arrangement of five triangles. Four such arrangements are shown in Fig. 3, but obviously the one in the upper left of the drawing is the most compact and therefore the best. As each of these triangles represents one face of a tetrahedron, it is necessary also to indicate the vertex opposite the face bearing the map. Thus the triangle 123, with the number 4 in its center, refers to the tetrahedron 1234, of which an orthogonal projection has been made onto the face 123. The complete drawing, lined for division of the components into 20 parts, is shown in Fig. 4.

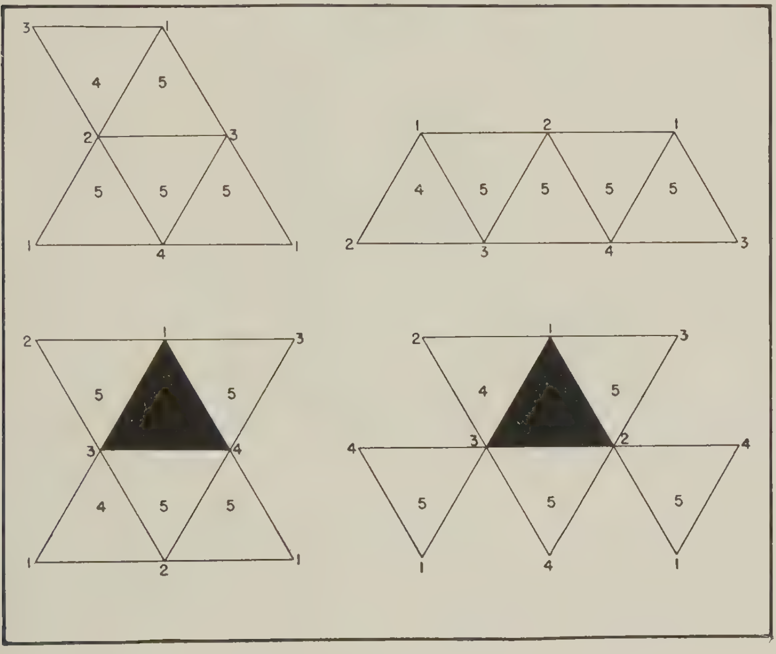

FIG. 3. Four arrangements of the bases of five bounding tetrahedra.

Exactly the same method is used in charting the quartets of 6 variables, but 15 instead of 5 triangles are required, on which to project the contour maps or space curves from the bounding tetrahedra. Only one satisfactory arrangement of these 15 triangles was found. The complete drawing, lined for division of the components into 20 parts, is shown in Fig. 5.

A method of direct projection from hypertetrahedra of four and five dimensions has also been mentioned. Consider first the hypertetrahedron of four dimensions, in which occur sets of points designated as (α, β, γ, δ, ϵ). It is desired to project orthogonally these points into three dimensions, so that the four-dimensional continuum which they define may be shown as surfaces. If one of these coordinates, say ϵ, is to be eliminated by the projection, it will be found that the quadriplanar coordinates of each of the projected points, referred to one of the bounding tetrahedra, will be $(\alpha+\epsilon/4)$, $(\beta+\epsilon/4)$, $(\gamma+\epsilon/4)$, $(\delta+\epsilon/4)$. A number corresponding to ϵ will be associated with each of the projected points, just as some number is associated with every point projected orthogonally from three into two dimensions. The coordinate eliminated from three dimensions represents altitude, and its various values constitute the data for drawing line contour maps in two dimensions. The coordinate eliminated from four dimensions represents a magnitude of the fourth dimension, and its various values constitute the data for drawing surface contour maps in three dimensions. Therefore in such orthogonal projections, surfaces instead of lines must be passed through or between the projected points. The resulting map is a series of contour surfaces, separated from one another by numerical values corresponding to the eliminated fourth dimension. This surface contour map, by its mode of construction, is automatically referred to one of the tetrahedra that bound the hypertetrahedron of four dimensions.

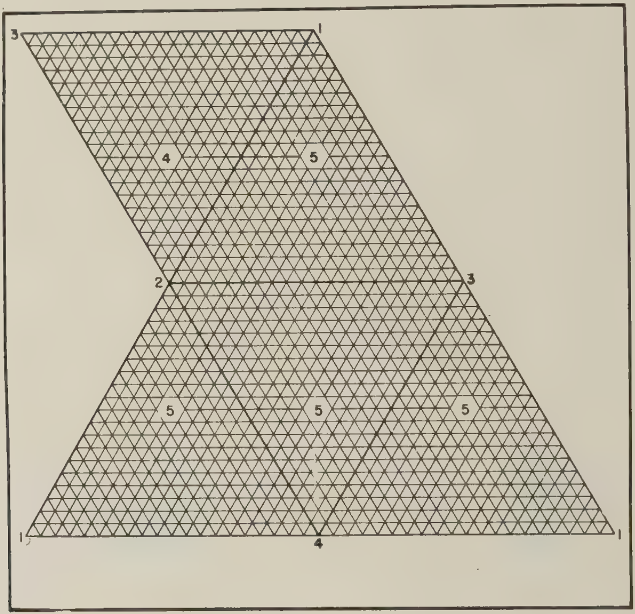

FIG. 4. Bases of five tetrahedra bounding a hypertetrahedron of four dimensions.

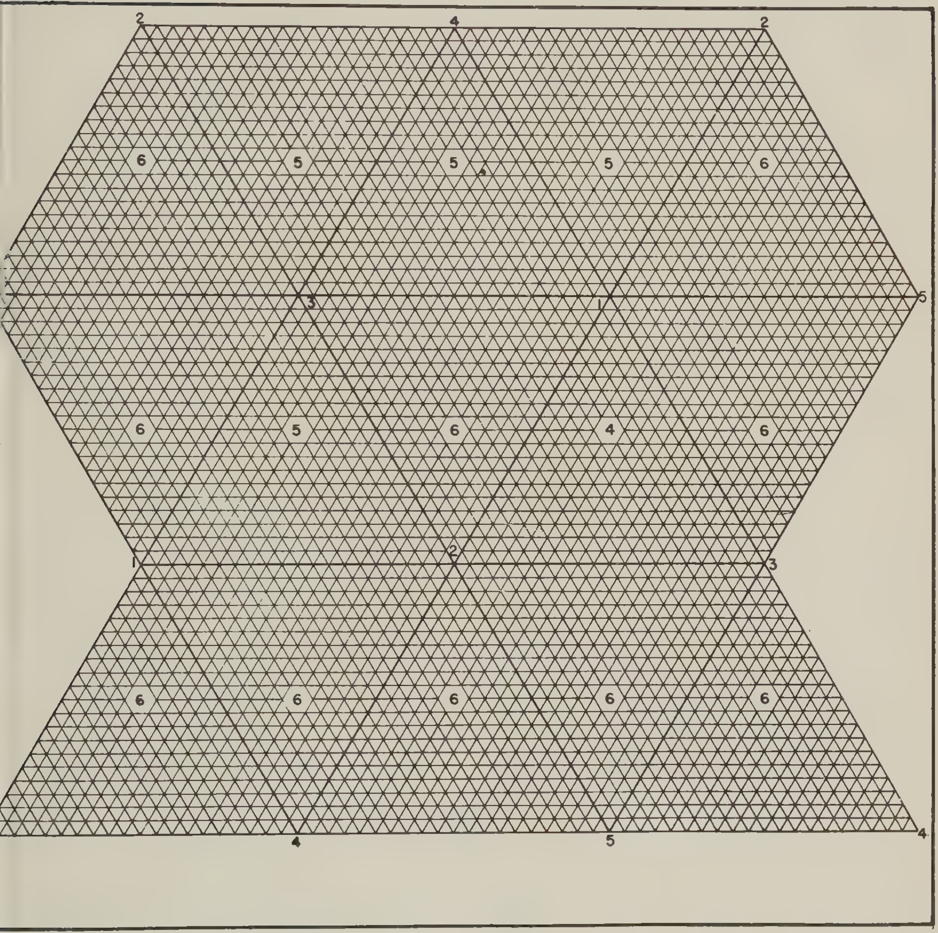

FIG. 5. Bases of fifteen tetrahedra bounding a hypertetrahedron of five dimensions.

This method is difficult of application, not on account of any difficulty in projecting orthogonally from four to three dimensions, but because the subparallel contour surfaces tend to obscure one another. A three-dimensional model must first be constructed, after which several photographs or perspective drawings will be required, in order to see all the contour surfaces and to visualize their relations to one another. One particular condition may exist, however, under which this method would be less troublesome. If the range in the numerical values of the fourth dimension were such that only four contour surfaces would be needed to show advantageously the experimental data, each of these four surfaces could be projected orthogonally onto a face of the tetrahedron of reference. A developed tetrahedron would thus result, showing four line contour maps that would represent the continuum referred originally to the hypertetrahedron of four dimensions.

A continuum defined by points having six coordinates, and designated as (α, β, γ, δ, ϵ, ξ), that is referred to a hypertetrahedron of five dimensions, may theoretically be reduced to surface contours in two different ways. By one method the variables would be recomputed to quintets, and would be charted in multiple with reference to the six bounding hypertetrahedra of four dimensions. As each hypertetrahedron of 4 dimensions is bounded by 5 tetrahedra, this technique would result in the preparation of 30 surface contour maps. A second method would be to make a direct orthogonal projection from five to four dimensions; and to re-project directly from four to three dimensions. The first step would result in a series of four-dimensional continua separated from one another by a magnitude of the fifth dimension; and the second step would result in the production of an exceedingly complex three-dimensional manifold, whereon both the fifth and the fourth dimensions would have to be shown in some manner. The first of these two methods is quite impracticable; the second is too abstruse for serious consideration.

Résumé

Methods are given in this paper for charting five or six variables in relation to the tetrahedra that bound hypertetrahedra of four and five dimensions. A method is also given for projecting directly from a hypertetrahedron of four dimensions into a single bounding tetrahedron; and two methods are outlined for projecting, indirectly and directly, from a hypertetrahedron of five dimensions into hypertetrahedra of four dimensions, and thence into figures of lower dimensions. The most practicable methods for charting five or six variables are by recomputing to triads or quartets, and by plotting these groups in relation to the triangles or tetrahedra that bound the hypertetrahedra.

X-RAY DATA ON SYNTHETIC MELILITES

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Abstract

Using a Geiger-counter recording spectrometer, powder diffraction patterns were obtained for 10 mixtures in the akermanite-gehlenite series. Graphs plotting change in *d*-spacing against composition for 10 lines of these patterns are shown whereby the relative amounts of akermanite and gehlenite in a melilite may be calculated from its *x*-ray pattern. In addition, unit cell dimensions for these tetragonal minerals were calculated, which show an increase in *a* and a decrease in *c* on proceeding from gehlenite to akermanite. These changes are explained on the basis of the known atomic structure of melilite.

Introduction

The melilites are a group of tetragonal minerals appearing in igneous rocks, in metamorphic assemblages, and in synthetic products such as crystallized blast furnace slags. Complete solid solution exists at high temperatures between the two principal melilite compounds, gehlenite, $Ca_2Al_2SiO_7$, and akermanite, $Ca_2MgSi_2O_7$ (1)(2). Other cations are also commonly present, especially sodium and divalent iron. The role of sodium in melilite crystals is not clear, as recently emphasized by Goldsmith (3). Divalent iron substitutes for magnesium in akermanite, replacement being complete in "iron-akermanite" (4).

The structure of a natural melilite crystal, which was largely an akermanite-gehlenite solid solution, was analyzed by Warren (5) who found two molecules in the unit cell with $a = 7.74$ Å and $c = 5.02$ Å.* The structure has SiO_4 tetrahedra linked in pairs, calcium is in eightfold coordination, aluminum and magnesium in fourfold.

As the present study was being completed, the work of Andrews (6) on the *d*-spacings and cell dimensions in akermanite, in gehlenite, and in three akermanite-gehlenite solid solutions appeared. The results given herein, insofar as they overlap the findings of Andrews, are in very good agreement with his data.

Results

Ten mixtures in the gehlenite-akermanite series were prepared from the pure oxides, melting four times with intermediate quenching to a glass and crushing. Each was crystallized by holding for several days at the temperature of the solidus, followed by several more days at a lower temperature. The glasses were shown to be uniform by their uniform refractive index, and the uniformity and complete crystallinity of the crystallized samples were checked petrographically.

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* Throughout this paper true ångstrom units are used, calculated according to the new grating wave lengths (Cu $K\alpha_1 = 1.5405$Å). Warren's values, actually in kX units, have been converted to ångstrom units (factor 1.002).

Powder diffraction patterns for the crystallized samples were obtained on the Norelco recording spectrometer using Cu-Kα radiation. The d-spacings thus obtained were assigned indices (hkl) and then used to calculate unit cell dimensions, which are shown in Table 1 and Fig. 1. Using these values for a and c, d-spacings were calculated for each plane

TABLE 1. UNIT CELL DIMENSIONS IN ÅNGSTROM UNITS AND RATIO c:a FOR THE AKERMANITE-GEHLENITE SOLID SOLUTION SERIES

Wt. % Akermanite	0	20	30	40	50	55	60	80	90	100
a	7.694	7.73	7.74	7.755	7.77	7.775	7.78	7.815	7.84	7.846
c	5.077	5.07	5.055	5.055	5.05	5.04	5.04	5.03	5.03	5.020
c/a	0.660	0.656	0.653	0.652	0.650	0.648	0.648	0.644	0.642	0.640

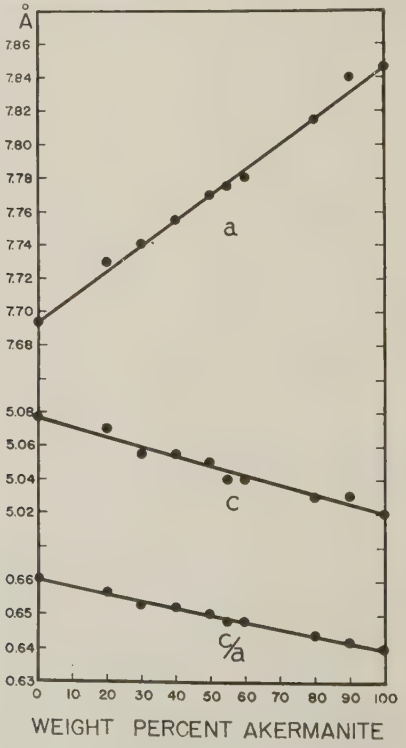

FIG. 1. Unit cell dimensions a and c in ångstrom units and ratio c:a for the akermanite-gehlenite solid solution series.

whose reflections were intense enough to appear. Table 2 gives, for pure gehlenite and akermanite, the d-spacings thus calculated together with the observed d-spacings and their estimated relative intensities showing the extent of agreement of the patterns with the assigned cell dimensions.

For the purpose of using x-ray patterns to determine the proportions of akermanite and gehlenite in a melilite, it is desirable to employ a simpler criterion than the change in unit cell dimensions, since the determination of these involves indexing a number of lines and making calculations. Correlating composition with d-spacing is the obvious simple procedure, but because of the simultaneous decrease in c with increase in a, as shown in Fig. 1, some pairs of lines in the pattern reverse their relative positions, while others show little change with composition. On the other hand, no one line would serve as a sufficiently precise measure of composition. Ten lines were selected which were distinct from any others throughout the range of compositions. These showed moderately large changes and were at the same time strong enough to appear in the majority of the patterns. In Fig. 2 the spacings for these 10 lines are plotted against composition, the solid line showing the d-spacings calculated

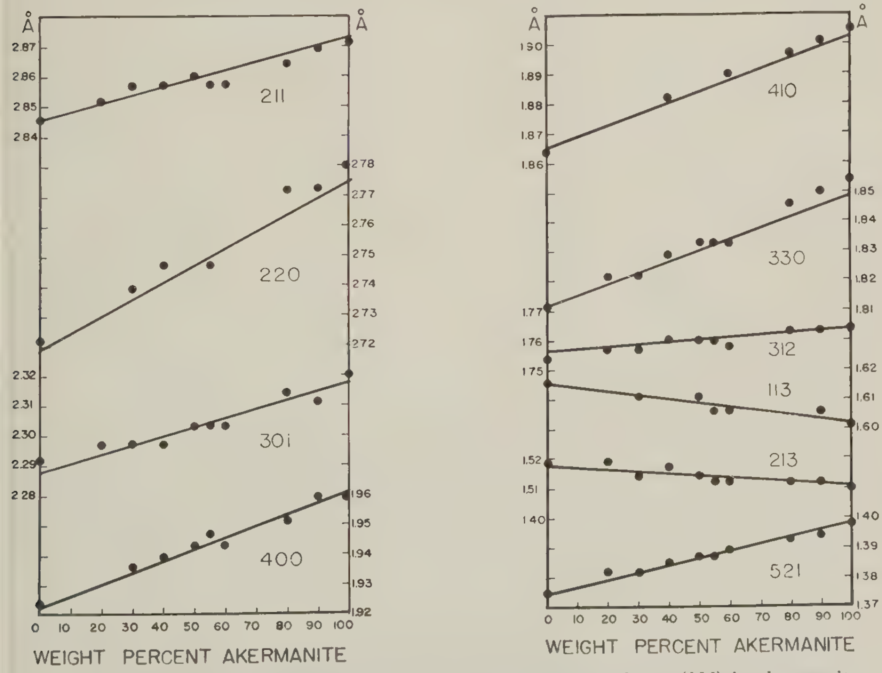

FIG. 2. Graphs showing manner of change in d-spacings of planes (hkl) in akermanite-gehlenite solid solutions. Circles represent experimentally determined points. The straight lines were drawn through points representing d-spacings calculated from the unit cell dimensions.

from the unit cell dimensions and the circles the observed d-spacings for each composition. Some points are missing where lines were too weak to be observed.

TABLE 2. CALCULATED AND OBSERVED d-SPACINGS IN GEHLENITE AND AKERMANITE

hkl	Calculated	Gehlenite Observed	Relative Intensity	Calculated	Akermanite Observed	Relative Intensity
110	5.440	5.456	4	5.555	5.55	11
001	5.071	5.082	4	5.013		
101	4.234	4.218	3	4.224	4.22	9
200	3.846			3.929	3.91	4
111	3.707	3.67	20	3.721	3.73	13
210	3.440	3.430	1	3.514	3.51	4
201	3.064	3.070	25	3.092	3.091	27
211	2.846	2.846	100	2.873	2.871	100
220	2.719	2.722	4	2.780	2.780	2
002	2.536	2.535	6	2.505	2.488	16
310	2.432	2.435	18	2.484		
102	2.409	2.404	22	2.387	2.391	9
221	2.396			2.429	2.429	5
301	2.288	2.292	13	2.321	2.320	9
311	2.193	2.195	1	2.225		
320	2.134	2.126	1	2.178		
202	2.117			2.112		
212	2.042	2.043	14	2.040	2.039	19
321	1.966	1.967	1	1.997		
400	1.923	1.924	6	1.963	1.959	5
410	1.866	1.864	4	1.905	1.905	7
330	1.813	1.812	8	1.851	1.854	9
312	1.756	1.754	34	1.764	1.764	27
420	1.720	1.723	5	1.756		
331	1.707			1.736	1.735	4
003	1.691			1.673	1.673	3
322	1.633	1.632	1	1.644	1.643	3
113	1.615	1.616	3	1.599	1.601	4
203	1.547			1.537	1.537	1
213	1.518	1.519	14	1.508	1.510	7
332	1.474	1.475	1	1.489	1.471	3
223	1.436	1.437	5	1.431	1.435	7
521	1.375	1.375	8	1.400	1.398	9
440	1.360	1.361	3	1.388	1.384	4
323	1.325	1.327	1	1.325		
502	1.316	1.316	1	1.332	1.335	3
600	1.282	1.282	1	1.309	1.308	3
004	1.268	1.267	3	1.253	1.256	9
413	1.253	1.253	4	1.255		
104	1.251			1.235	1.242	3

To use these graphs the percentage akermanite is read off for each of the 10 lines of the pattern or as many of the ten as show up. The average of these 10 (or less) percentages is taken as the final value. The precision of this method is estimated at ±2.5% akermanite.

Discussion

The above data agree very closely with those of Andrews. One discrepancy is that his curves of a and c against composition show a slight curvature. In our case, these plots are straight lines, within experimental error. However, the closeness of fit is probably not good enough to justify definite conclusions about adherence to Vegard's law and ideality of melilite solid solutions. It is clear, nevertheless, that no large departure from ideality exists.

The deviation of Warren's values for a and c is outside of the experimental error. That is, his value of 7.74 Å for a indicates about 25% akermanite while his value for c is equal to that for pure akermanite. Some of Warren's intensities deviate very markedly from those found for the gehlenite-akermanite series. Inasmuch as Warren used a crystal of natural melilite which would contain other ions in addition to those present in akermanite and gehlenite, the explanation for these differences is undoubtedly related to the presence of these other ions.* An analysis of the structures of pure gehlenite and akermanite might result in a change in some of the coordinates and interatomic distances but probably not in any of the fundamental features of the structure.

The seemingly remarkable decrease in the c dimension which accompanies the increase in a on going from gehlenite to akermanite has a simple explanation on the basis of Warren's structure. Close study of the structure (5), (7), shows that in the 001 plane the atoms are in close contact in the planes passing through the Mg positions. In the c direction, however there are gaps in the structure in the axes passing through the Mg positions. Consider now the effect of substituting Mg+Si for 2Al. In the first place, the a dimension should be increased by an amount approximating the difference between the increase in ionic radius of Mg over Al and the decrease in ionic radius of Si over Al, because of the close packing in the a direction. A purely geometrical calculation based on the ionic radii given by Evans (8), corrected for fourfold coordination, gives an increase of 0.23 Å for a as compared with 0.152 Å actually observed. The effect of the larger Mg ion on c, however, is nullified by the presence of the gaps in the structure between the Mg ions in the *c* direction, into which the oxygen ions surrounding the Mg can move without expanding the cell dimensions in that direction. Thus the only effect is the contraction due to substitution of Si for Al which is calculated as 0.14 Å compared with 0.057 Å actually found. The lack of a quantitative check could be due to polarization effects, which have not been taken into account.

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* The melilite crystal used by Warren was from Capo di Bove. The composition of a representative melilite from this locality analyzed by Damour and discussed by Schaller (*U. S. Geol. Survey, Bull.* **610**, 124 (1916)) is as follows: 38.34 SiO_2, 8.61 Al_2O_3, 32.05 CaO, 2.12 Na_2O, 6.71 MgO, 10.02 Fe_2O_3, 1.51 K_2O. It is considered possible by Schaller that a part of the iron existed in the melilite in the ferrous state.

Densities calculated from these unit cell dimensions are compared below with the experimental values determined by Ferguson and Buddington (1):

	gehlenite	*akermanite*
Calculated density	3.031±0.01	2.922±0.01
Experimental density	3.038	2.944

ACKNOWLEDGMENTS

The melilites used in this study were prepared by the junior author in 1940 while on the staff of the Geophysical Laboratory of the Carnegie Institution of Washington. The writers wish to thank Dr. L. H. Adams, Director of the Geophysical Laboratory, for releasing samples of these preparations for further study at The Pennsylvania State College. The writers wish also to thank Professor T. F. Bates for his helpful suggestions during the course of this study and Professor George Tunell for his criticisms of the manuscript.

REFERENCES

(1) FERGUSON, J. B., AND BUDDINGTON, A. F., *Am. Jour. Sci.*, **50,** 131–140 (1920).
(2) OSBORN, E. F., AND SCHAIRER, J. F., *Am. Jour. Sci.*, **239,** 715–763 (1941).
(3) GOLDSMITH, J. R., *Jour. Geol.* **55,** 400–403 (1947); **56,** 437–447 (1948).
(4) BOWEN, N. L., SCHAIRER, J. F., AND POSNJAK, E., *Am. Jour. Sci.*, **24,** 262–263 (1933).
(5) WARREN, B. E., *Zeit. Krist.*, **74,** 131–138 (1930).
(6) ANDREWS, K. W., *Mineral. Mag.*, **28,** 374–379 (1948).
(7) BRAGG, W. L., Atomic Structure of Minerals, Cornell University Press, 177 **(1937).**
(8) EVANS, R. C., Crystal Chemistry, Cambridge University Press, 171 **(1946).**

THE VARIABLE INVERSION TEMPERATURE OF QUARTZ AS A POSSIBLE GEOLOGIC THERMOMETER

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Abstract

The high-low inversion temperature of quartz has been found to vary as much as 1.90° C. The inversion temperature varies inversely with the temperature of formation and therefore may become a useful geologic thermometer.

Introduction

The high-low inversion temperature of quartz has been investigated by many observers. For a comprehensive review of these studies the reader is referred to Sosman[1] (1927). The most accurate measurements of the inversion temperature are those by Bates and Phelps[2] (1921) who suggested using the inversion temperature as a fixed point on the thermometric scale. They found the rising-temperature inversion to be 573.3±0.1° C.

The inversion temperature as a function of the geologic history of the quartz has not been investigated so far as the writer is aware, although Sosman suggested that such a study would be of considerable interest. The present report deals with a preliminary study of that relation.

Method

The quartz was crushed, sieved through a 35 mesh screen, and collected on a 200 mesh screen after which it was treated with boiling hydrochloric acid for 30 minutes, washed, and dried at 110° C. The high-low inversion temperature was measured by means of time-temperature heating curves using chromel-alumel thermocouples. The thermoelement junction was imbedded in 1.5 grams of powdered quartz.

Temperature measurements were made with a White potentiometer that gave readings on a standard quartz that were reproducible to ±.04° C. This degree of reproducibility could be obtained only by taking special care to place the charge and thermoelement leads in exactly the same position in the furnace for each experiment and to have the cold junction portion of the leads immersed to the same depth each time. All determinations were made by heating the powder at a uniform rate of 1° C. per minute through the inversion region and recording the temperature at 15-second intervals. The inversion temperature was taken as the intersection of two straight lines drawn in the manner shown in Fig. 1.

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[1] Sosman, Robert B., The properties of silica: *Am. Chem. Soc., Monograph No.* **37** (1927).

[2] Bates, F., and Phelps, F. P., The new fixed point on the thermometric scale: *Phys. Rev.* (2) **18,** 115–116 (1921).

The present investigation is concerned with differences in the inversion temperature and not the actual temperature of the transition, therefore

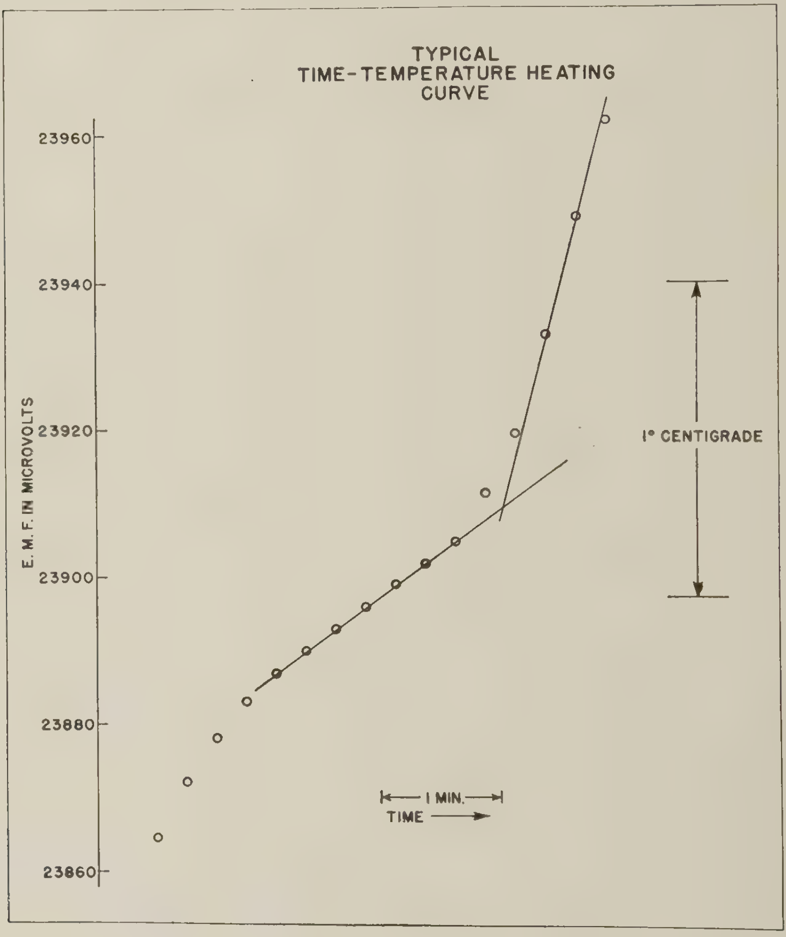

Fig. 1

no attempt has been made to fix the measurements on the thermometric scale.

All determinations reported are temperature differences between a "reference" quartz and the unknown. A large single crystal of quartz from Minas Gerais, Brazil, was selected as a reference. It is likely that the reference quartz used in this work has the same geologic origin as the material used by Bates and Phelps, therefore presumably has an inversion temperature of 573.3±0.1° C. One half of the crystal was crushed and used in the determinations, the remainder being saved for other investigations.

Each determination was made as follows: Three time-temperature heating curves were run on the reference quartz, the last two being made without cooling more than a few degrees below the transition. The reference quartz was then removed and the unknown immediately placed in the furnace and three time-temperature curves were made as before. To check any drift in the potentiometer the reference quartz was again placed in the furnace and rerun three additional times. In all determinations the value of the third run of the second set of runs on the reference quartz was within 0.08° C. of the first, and the mean of the two values was accepted. A typical series of experiments is shown in Table 1.

Table 1. Determination of Difference in Inversion Temperature of Standard and Unknown

Run	*Standard*	*Unknown*	*Standard*
1	23845.6	23829.9	23847.6
2	23842.0	23824.3	23842.0
3	23840.2	23823.0	23841.2

Standard	23840.7
Unknown	23823.0
	17.7 or 18 Microvolts difference

It was necessary to make three time-temperature curves for each determination because the first and second runs on a sample that had been cooled to room temperature were always somewhat higher than subsequent runs (one exception to this was found). After the third run through the transition the temperature of the inversion was constant within the experimental error and this value was accepted.

Investigations of the inversion by means of cooling and differential curves have not been carried out. The interrelations between heating, cooling, and differential curves should provide much useful additional information.

Results

The inversion temperature of 36 quartz samples has been determined with respect to the reference quartz (Table 2). Inversion temperatures 0.60° C. above, and 1.30° C. below the reference have been found.[3]

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[3] It should be pointed out that the value of quartz for calibration in routine thermal analysis as recently proposed by Dr. George T. Faust (*Am. Mineral.*, **33**, 337–345, 1948) is in no way affected by the variations in the inversion temperature reported here.

TABLE 2

No.	Type of Occurrence	Locality	Remarks	±ref. quartz
1	Novaculite	Missouri		+18
2	Euhedral crystals in solution cavities in limestone	Carrara, Italy		+17
3	Vein quartz	Brazil	Easily twinned by sawing	+15
4	Euhedral crystals from vug in limestone	Keokuk(?), Iowa	Pronounced lineage	+15
5	Quartz from Alpine-type vein	Switzerland	Smoky twisted	+14
6	Vein quartz	Brazil	Smoky, same crystal as spec. 9	+12
7	Vein quartz	Brazil	Easily twinned	+12
8	Euhedral crystals from vug in limestone	Herkimer Co., New York		+11
9	Vein quartz	Brazil	Clear, same crystal as spec. 6	+10
10	Euhedral crystal from vug in limestone	Herkimer Co., New York	Different source from 8	+10
11	Quartz vein in biotite gneiss	Washington, D. C.		+ 5
12	Quartz vein	Guanajuato, Mexico	Lineage present, amethyst	+ 5
13	Quartz-ankerite vein in marble	Medicine Bow Mts., Montana		+ 3
14	Quartz vein in mica schist	2 miles North of Keystone, S. D. on Hwy. 16		+ 2
15	Quartz vein	Hot Springs, Ark.		+ 1
16	Glassy white quartz core of pegmatite	New York Mine, Black Hills, S. D.		0
17	Quartz vein containing andalusite	Black Hills, S. D.		0
18	Harney Peak Granite	North of Mt. Rushmore, Black Hills, S. D.		0
19	Pegmatite in Harney Peak granite	North side of Sylvan, Lake, Black Hills, S. D.		− 2
20	Pegmatite in Harney Peak granite	South of Grizzly Bear Camp Grounds, Black Hills, S. D.		− 5
21	Graphic granite	Bradbury, Maine		−12
22	Rhyolite tuff	New Mexico		−14
23	Biotite granite	Wallace Cove, Head Harbor Island, Jones Port, Maine		−17
24	Probably pegmatite	Brazil	Citrine quartz	−19

TABLE 2—(*continued*)

No.	Type of Occurrence	Locality	Remarks	±ref. quartz
25	Gray quartz from quartz-spodumene zone of pegmatite	Helen Beryl Mine, Black Hills, S.D.		−21
26	Graphic granite	Minot, Maine		−23
27	Quartz core of pegmatite	Etta Mine, Black Hills, S. D.		−24
28	Rhyolite	New Mexico	National Mus. 102458	−26
29	Pegmatite	West of New York Mine, Black Hills, S. D.	Small offshoot (?) of N. Y. pegmatite	−26
30	Pegmatite	Jones Port, Maine	Specimen taken near 23	−28
31	Rhyolite	Colorado	Nevadite	−29
32	Rhyolite	Locality unknown	Euhedral crystal	−38
33	Epithemal (?) vein	Cripple Creek, Colorado		−40
34	Pegmatite	Probably Maine	Rose quartz	−52
35	Synthetic—grown in dilute NaOH solution at 300° C. and 1000 kg./cm.^{2} pressure			+24
36	Synthetic—grown in sodium tungstate melt at 800° C.			−12

Phenocrysts of quartz from five different rhyolites, presumably formed at high temperature, have transition temperatures below the reference quartz. Moreover one sample of quartz grown in the laboratory at 800° C. also inverted below the reference. On the other hand five samples believed to have grown at low temperature (from vugs in limestone) have inversion temperatures higher than the reference, as does one sample grown in the laboratory at 300° C. The relative temperature of formation of the remainder of the specimens is not known as they are from granites, pegmatites and quartz veins. Fig. 2 illustrates the relative temperatures of inversion of these samples.

Observations of geological significance may be summarized as follows:

(*a*) All quartz specimens whose geologic environment indicates low temperature of growth and one synthetic at 300° C. invert at higher temperatures than the reference quartz.

(*b*) All quartz from rhyolites and one synthetic at 800° C. invert at temperatures below the reference sample.

(*c*) All specimens whose morphology indicates low quartz invert at the same temperature as or at a higher temperature than the reference quartz.

(*d*) All specimens having recognizable lineage invert at higher temperatures than the reference. This inverse relation between lineage and tem-

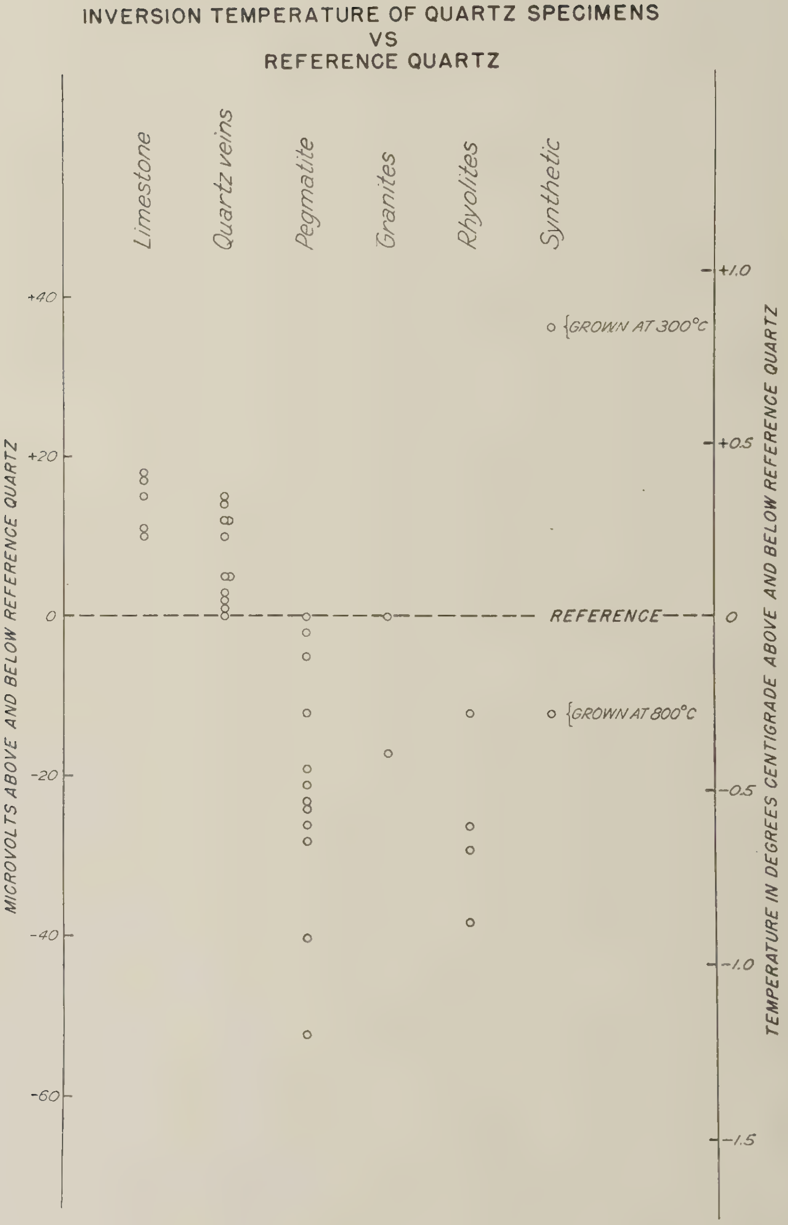
INVERSION TEMPERATURE OF QUARTZ SPECIMENS
VS
REFERENCE QUARTZ
Limestone
Quartz veins
Pegmatite
Granites
Rhyolites
Synthetic
GROWN AT 300°C
GROWN AT 800°C
REFERENCE
MICROVOLTS ABOVE AND BELOW REFERENCE QUARTZ
+40
+20
0
-20
-40
-60
TEMPERATURE IN DEGREES CENTIGRADE ABOVE AND BELOW REFERENCE QUARTZ
+1.0
+0.5
0
-0.5
-1.0
-1.5

Fig. 2

perature of formation has been reported for other crystals.[4] It is unfortunate that a quantitative method of evaluating the magnitude of lineage has not been devised.

(*e*) Two specimens of chert showed no break in the heating curve although x-ray analysis indicates that both samples are quartz.

(*f*) All specimens except number 24 inverted at a higher temperature on heating through the inversion from room temperature than on heating from a few degrees below the inversion temperature. In other words there appears to be some type of readjustment on cooling to room temperature that does not take place on cooling only a few degrees below the transition temperature. Much additional experimental work will have to be carried out to exclude experimental uncertainties before the significance of this observation can be evaluated.

Theoretical Considerations

Variability of the inversion temperature of quartz is probably the result of solid solution. Knowledge of the amount and kind of "impurities" must await careful spectrographic analysis.

Solid solution can raise the inversion temperature, lower it, or leave it unaffected, depending on the solubility relations between the two modifications of the crystal and the material entering into solid solution. If the solubility is greater in the high temperature modification, the inversion temperature will be lowered; whereas greater solubility in the low temperature form will raise the transition temperature.

The greater specific volume of the high temperature modification suggests that solid solution, especially of the interstitial type, would be greater in the high temperature form, with consequent lowering of the transition temperature. This is the relation actually found.

Quartz is a unique mineral in that it reputedly does not vary in composition despite its wide geologic distribution and the variability of the chemical environment in which it has grown. However, the possibility that small amounts of other elements may enter into solid solution cannot be excluded. A certain amount of interstitial solid solution seems probable, and substitutional solid solution does not appear to be improbable. Germanium, which is a likely candidate for substitutional solid solution, has been reported in small amounts in quartz.[5] Also, Ba, Al, and

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[4] Smith, F. G., Lineage structure and conditions of deposition of pyrite: *Econ. Geol.*, **37**, 519 (1942).

Tuttle, O. F., and Twenhofel, W. S., Effect of temperature on lineage structure in some synthetic crystals: *Am. Mineral.*, **31**, 569–573 (1946).

[5] Goldschmidt, V. M., and Peters, C., Zur Geochemie des Germaniums: *Nachr. Ges. Wiss. Göttingen, Math.-Phys. Kl.*, **141** (1933).

Ti have been reported in quartz from granitic rocks in amounts up to 0.90%.[6] These impurities, if present in solid solution, might be sufficient to change the inversion temperature appreciably. Theoretically strain, such as may be present in the quartz from mylonitic rocks, could affect the inversion characteristics. An investigation of this possibility is being carried out.

Conclusions

The inversion temperature of quartz believed to have grown at low temperature is higher than specimens believed to have grown at high temperatures. The same contrast is shown by quartz grown in the laboratory at measured temperatures. If this inverse relation between inversion temperature and temperature of formation is found to be universally valid the quartz inversion will become a valuable geologic thermometer especially when calibrated by quartz grown at known temperatures and pressures in the laboratory. Solid solution is believed to be the most likely cause of the variable transformation temperature.

Acknowledgments

The writer is indebted to Drs. N. L. Bowen and M. L. Keith for many helpful suggestions concerning this investigation. Thanks are due also Drs. Clifford Frondel of Harvard University, W. F. Foshag of the National Museum, and Felix Chayes of this Laboratory for providing many of the quartz specimens used in this work.

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[6] Bray, J. M., Spectroscopic distribution of minor elements in igneous rocks from Jamestown, Colorado: *Bull. Geol. Soc. Am.*, **53,** 765–814 (1942).

OBSERVATIONS ON TWO PRECISION LATTICE MEASUREMENTS OF PYRITE FROM LEADVILLE, COLORADO

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ABSTRACT

Two recent, independent determinations of the cube-edge of pyrite from the same locality gave rather divergent results. A study of the two papers indicated that the differences are apparent rather than real—in fact, the results are in remarkable agreement with each other. It is thought that such agreement in the light of known variations in the properties of pyrite may be of some significance to the geologist.

INTRODUCTION

Precision lattice determinations of minerals are not yet common and not always practicable. Generally, results of high accuracy may be thought to serve no particular purpose but for certain mineralogical problems, and possibly some geological ones, precision data become desirable. The minerals of the cubic system whose paramaters can so readily be determined by *x*-ray powder methods with great accuracy, deserve greater attention in this respect. Among these minerals there are a number which by virtue of their significance in ore deposits, attract attention, e.g. pyrite; gold; galena; chromite; magnetite; uraninite, etc.

It was disconcerting, however, to find that on separate samples of pyrite from the same locality, the following results have been published by two prominent teams of mineralogists:

PYRITE, LEADVILLE, COLORADO

$a_0=5.4079 \pm 0.0005$Å	Peacock and Smith (1941)
$a_0=5.40667 \pm 0.00007$Å	Kerr, Holmes and Knox (1945)

Data of the accuracy claimed here are almost totally lacking for minerals; Kerr et al. do not try to explain the difference in the two cube-edge measurements and the object of this paper is to try to reconcile these results if possible.

CHEMICAL ASPECTS

Small variations in the composition of pyrite are known to exist and it has been shown that such differences affect the value of the unit cell (Peacock and Smith; Bannister and Hey, etc.). Peacock and Smith selected their Leadville sample because it approached perfection both physically and chemically; while the Kerr team tacitly assumed such perfection as their result is used to typify pyrite.

In the absence of any other possibilities of errors, both results of the

Leadville pyrites could be accepted as correct on the basis that the sample examined by Kerr and co-workers was chemically imperfect: a deficiency of sulphur in their specimen could readily account for the lower result. Smith (*Am. Mineral*, **27,** p. 9) records that ". . . pyrite may vary from $FeS_{2.00}$ to $FeS_{1.94}$ and still contain essentially nothing but iron and sulphur."

A corollary of importance would be that there are at least two distinct types of pyrite at Leadville.

TEMPERATURE CONSIDERATIONS

In neither paper are temperature effects considered. Reliable linear coefficients of thermal expansion of minerals are difficult to find; the best value is probably given in the *G.S.A.* publication "Handbook of Physical Constants" (Special papers No. **36**). One arrives at a value of nearly 0.00005 Å per degree centigrade in the variation of the cube-edge of pyrite. The degree of accuracy claimed by Kerr et al., viz. 0.00007 Å, becomes obviously untenable for it would mean that a variation of only $1\frac{1}{2}°$ C. would exceed the limits of total error admitted. Very special temperature safeguards over the period of radiation would be necessary in order to obtain the accuracy claimed and from such considerations one must conclude that the Kerr value cannot possibly exceed five significant figures, and at best can be given as:

$$a_0 = 5.4067 \pm 0.0001 \text{ Å}.$$

A "room temperature" difference of at least 12° C. would therefore fully account for the divergence in results if the limits of errors in both values are fully extended. It is, however, more likely that about 25° C. have to be assumed to represent the difference in temperatures in the two laboratories and this is hardly likely even when taking the heating effect of the *x*-ray units into account.

The effect of temperature certainly cannot be neglected and constitutes an important source of error in precision work of minerals with a relatively high co-efficient of expansion. It is improbable that temperature alone could explain the two divergent values.

WAVELENGTHS

Peacock and Smith state the wavelengths used by them, and these are the corrected Siegbahn units, i.e. Ångstroms; but they are not consistent in this usage as for their calibration they use the "Strukturbericht" value of the cube-edge for copper which although given in Ångstroms, is really in kX-units.

Kerr and his colleagues do not mention what wavelength value was used but give their results in Ångstroms. There are sufficient data to check this and it is found that kX-units have in fact been used: their result is therefore not directly comparable with the Peacock-Smith figure as given.

It is relevant here to quote from a letter to "Nature" (VI, 151, p. 502, 1943) written by Lipson and Riley of the Cavendish Laboratory, which deals with this sort of looseness in the expression of *x*-ray units: " . . . it has been the custom to quote all results as though they were in Ångstrom units. . . . May we suggest the adoption of the following conventions? When an accuracy not better than 0.1% is claimed, the result should be given in Angstrom units, but for higher accuracy . . . in X units. The lattice parameter for iron could be given as 2.86 Å or 2860.4 X units, but not as 2.8604 Å. The wavelength adopted should always be explicitly stated. . . . "

These are sound conventions which are appreciated after examining the two papers under discussion.

Bearing in mind the remarks made in respect of temperature correction, the cube-edge for the pyrite sample from Leadville given in the paper by Kerr et al. becomes:

5406.7 ± 0.1 X-units.

Had Peacock and Smith given their result for the Leadville sample in X-units, the value would have been:

5407.0 ± 0.5 X-units.

Within the limits of error the two results obtained by independent teams of workers are now found to be in very good agreement.

SYSTEMATIC ERRORS

Every experimental method is subject to certain inherent errors and it remains to consider this aspect in the two determinations. In equipment and in the method of elimination of systematic errors, Kerr and his colleagues have closely followed Jette and Foote whose lattice determinations are considered amongst the best available.

The corrections applied by Peacock and Smith after a single calibration using pure copper as a standard, and with a confusion in wave-lengths, in respect of the cube-edge value for copper, invite criticism. The correction graph based on copper requires a slight extension in a straight line to cope with the higher angles of pyrite.

In order to test out this empirical type of correction graph evolved by Peacock and Smith, the writer prepared similar graphs using highly purified gold and silver as standards, a similar camera but different radiation, viz. copper. A rough parallelism could be noted between the three graphs but the corrections appeared to be a function of the standardizing substance used.

As the well established extrapolation technique worked out by Bradley and Jay (*Proc. Phys. Soc.*, **44,** p. 563, 1932), is more accurate, rapid and convenient, there is nothing to be gained by the method employed by Peacock and Smith. From their data it is possible to ascertain the glancing angles they must have actually measured on their film; using these—a very small error may have been introduced in taking readings off the reconstructed correction graph—and the following wavelengths:

$$\text{Fe-K}_1 = 1932.076 \text{ XU}$$
$$\text{Fe-K}_2 = 1936.012 \text{ XU},$$

the cube-edge of pyrite for the three (*hkl*) values were plotted against $\cos^2 \theta$ and extrapolated to zero error. This gave the final value, with the plotted points falling on a good straight line, as:

$$a_0 = 5406.6\text{XU}.$$

This result is considered to be nearer the true value than the one obtained by converting the Peacock-Smith figure into X units.

The limits of error have not been accurately assessed, but are considered to be now much less than assumed by Peacock and Smith. Based on the experience of the writer, this error will probably not exceed 0.3 XU; or dividing by a thousand, 0.0003 KXU.

CONCLUSIONS

The findings of the two papers may now be summarized in this way:
Pyrite, FeS_2, Leadville, Colo., at "Room Temperature".

$a_0 = 5.4066 \pm 0.0003$ KXU. . . . . .Peacock and Smith (1941).
$a_0 = 5.4067 \pm 0.0001$ KXU. . . . . Kerr, Holmes, and Knox (1945)

These determinations show a truly remarkable agreement and one is inclined to assume that, therefore, the two samples were chemically identical and that the temperatures at the times of exposure were probably very similar.

Peacock and Smith show that the introduction of nickel, which is a well known "contaminant" of pyrite, appreciably raises the length of the cube-edge while a deficiency of sulphur somewhat lowers the value. This latter phenomenon is shown by the other measurements of a pyrite given in their paper, which when re-determined and extrapolated to zero error as with the Leadville sample, gives the following result:

Pyrite, $Fe_{1.98} \pm 0.01$, Elba, at "Room Temperature"
$a_0 = 5.4050 \pm 0.0003$ KXU

The pyrites from the two widely separated localities are therefore clearly different and this difference is readily measurable and recognizable by a comparatively simple *x*-ray technique

Peacock and Smith have shown the high accuracy obtainable with a Debye-Scherer camera using the Straumanis method of film mounting. If to this is added the graphical method of Bradley and Jay for the elimination of systematic errors—and perhaps, the correction for refractivity, which is usually neglected—cube-edges can be determined with the highest precision. The difficulty of overcoming temperature effects may well prove a barrier to increased accuracy with focusing types of cameras -especially where the samples possess relatively high coefficients of expansion, and require lengthy exposures.

There is clearly a need for further accurate data on the Leadville pyrite which because of its apparent perfection could become a "standard." Pyrite is very common, and is associated with economic mineral occurrences of diverse kinds. From the work of Smith it is known that there are large variations in the properties of pyrite. It would be very useful to the geologist if he could differentiate between various pyrites with ease and certainty, and this seems quite feasible by powder *x*-ray diffraction, preferably linked with spectrographic data. Such an approach allows one to work with minute quantities and to obtain quantitative results which facilitate correlation. It is reasonable to assume that somewhere the mineral pyrite may well prove as useful as an "indicator fossil"—it remains to collect the relevant data.

REFERENCES

Bannister, F. A., and Hey, M. H. (1940), Bravoite from Mills Close Mine, Derbyshire: *Mineral. Mag.*, **25**, 609–614.

Bradley, A. J., and Jay, A. H. (1932), A method for deducing accurate values of the lattice spacing from *x*-ray powder photographs taken by the Debye-Scherer method: *Proc. Phys. Soc.*, **44**, 563–579.

Kerr, P. F., Holmes, R. J., and Knox, M. S. (1945), Lattice constants in the pyrite group: *Am. Mineral.*, **30**, 498–504.

Peacock, M. A., and Smith, F. G. (1941), Precise measurements of the cube-edge of common pyrite and nickeliferous pyrite: *Univ. Toronto Studies, Geol. Ser.* No. **46**, 107–117.

Smith, F. G. (1942), Variations in the properties of pyrite: *Am. Mineral.*, **27**, 1–19.

PETROLOGY OF THE NEPHELINE AND CORUNDUM ROCKS OF SOUTHEASTERN ONTARIO

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Abstract

A speculative working-hypothesis is offered to account for the genesis of the well-known nepheline- and corundum-bearing gneisses of southeastern Ontario. Field evidence appears to indicate that most of the nepheline and corundum rocks of this area were derived from pre-existing dark gneisses of the Grenville series, by reaction with hydrothermal emanations of magmatic origin, which were released by the crystallization of normal granitic masses and carried the usual complement of silica, alumina, alkalies, and mineralizers. As the Grenville rocks were traversed by these emanations, silicates were developed in some of the dolomitic marble, and some of the basic dark gneisses were converted to syenite-like gneisses. During the resulting reactions the emanations lost silica but gained carbon dioxide. Thus enriched in alkalies and alumina, the emanations continued to traverse and react with the dark gneisses, converting calcic feldspar to alkali feldspars and nepheline (the lime being removed as calcite). Later emanations, following the same routes, lost less silica to the country rocks and reacted with some of the already-formed nepheline to produce alkali feldspars and corundum. Where siliceous emanations or granitic pegmatites invaded partially altered dark gneisses, calcic feldspars were converted to alkali feldspars and corundum. Most of the nepheline and corundum rocks are gneissic, and are conformable in structure with the surrounding Grenville gneisses of normal type. Locally, the gneissic structures of the nepheline and corundum rocks have been destroyed by recrystallization, with considerable coarsening of grain size. Pre-existing variations in composition, structure, and texture influenced the localization of the nepheline and corundum.

Introduction

This paper was written to focus attention on an important geological problem requiring concerted study by capable structural geologists, mineralogists, and petrologists. A solution which is acceptable to all of these will add much to the science of petrology.

The nepheline and corundum rocks under discussion occur in a region that is now well-known in geological literature, and which includes part of the Haliburton-Bancroft area of Ontario, mapped by Adams and Barlow (1910) at the beginning of this century. Their maps and reports present an excellent general picture of the geological environment of the nepheline and corundum rocks. Following Adams and Barlow, many others have examined and described individual occurrences or small areas within the region. As yet, however, no generally acceptable theory of genesis which includes all the unusual rocks that occur in the region has been established.

The writer spent several years in the region and became familiar with its diverse and unusual rock types and mineral occurrences by collecting mineral specimens for museums, and engaging in the reconnaissance mapping and detailed exploration of deposits of economic minerals, including nepheline and corundum, feldspar, magnetite, graphite, fluorite, molybdenite, beryl, uraninite, and other rare-element minerals. On the basis of this experience and the published data of others, a working hypothesis has been developed to account for the genesis of the nepheline and corundum rocks. This hypothesis is entirely speculative and is being presented, not for immediate acceptance or rejection, but to spur others to go into the region and to map and study the occurrences in the detail required for a satisfactory theory of genesis.

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The writer has drawn heavily from the compilations and used freely

the theories of S. J. Shand and R. A. Daly. The work of F. D. Adams and A. E. Barlow formed the background for the studies that have been made in the region.

Location and Geological Setting

The rocks containing nepheline and corundum crop out as elongated masses, most of which are within an area about 100 miles long and 10 miles wide, crossing Renfrew, Hastings, and Haliburton Counties, Ontario. The long axis of the area is roughly parallel to and slightly north of the line joining the cities of Ottawa and Toronto.

Most of the region is underlain by rocks of the pre-Cambrian Grenville series. In the southern portion, granite crops out as scattered, stock-like bodies. Northward, the bodies of granite are more numerous and larger, so that in the northern portion granitic material predominates, and Grenville rocks form roof pendants and inclusions. Thus, observing the outcrops while travelling northward across the region is similar in effect to seeing the rocks at increasingly deeper levels below the starting point.

The Grenville series in the region consists of very thick dolomitic marble, with abundant intercalated dark gneiss, generally amphibolite, less commonly paragneiss. Highly siliceous sediments are uncommon. Some of the varieties of amphibolite very obviously owe their origin to the silication of dolomitic marble. However, most of the dark gneisses appear to represent highly metamorphosed equivalents of the basic intrusives and extrusives, which are common just to the south of this region, but absent within it. Satterly (1944) noted gradations from typical greenstone, showing pillow-structures, to amphibolite, with the transition occurring near the southern limit of the region under discussion. Plagioclase and hornblende are the principal constituents of the dark gneisses. In some varieties, biotite or pyroxene takes the place of hornblende. Quartz is scarce or absent. The feldspars of six amphibolites were determined by Adams and Barlow (1910), who found that two of the amphibolites contained feldspar intermediate in composition between andesine and labradorite, two contained medium labradorite, and two contained calcic labradorite. Keith (1939) noted that andesine is the major constituent of the Grenville schist which forms the host rock of the Blue Mountain nepheline belt.

The Grenville series was folded, with development of axes trending about N 30° E, and intruded by large granitic masses. These intrusives appear to have domed the country rocks, and primary foliation within the intrusives parallels the contacts. The contacts show evidence of the stoping-off and penetration of country rocks by the magma, and there are extensive indications of contamination of the magma by the addition of country rocks.

The marble was much altered by the intrusives, with development of phlogopite, diopside, tremolite, scapolite, sphene, apatite, etc. Some of the dark gneisses adjacent to the intrusives have had lit-par-lit additions of granitic and syenitic magma. Granitic pegmatites are common; many are very coarsely crystalline, and carry concentrations of rare-element minerals. Veins and nests of coarsely crystalline calcite are widely distributed. The walls of these veins are lined with well-developed crystals of the various rock-forming minerals, which have grown outward into the calcite.[1] Magnificent specimens from this region are displayed in mineralogical museums throughout the world.

Syenite dikes and sills are fairly common.

Description of the Nepheline and Corundum Rocks

Occurrence

In this region, the zone of medium intensity of intrusion and metamorphism appears to have been most favorable for the development of nepheline and corundum, since these minerals are found only in rocks which reflect those conditions. Some of the occurrences show a peripheral distribution around, and not far distant from, the margins of granitic bodies.[2]

Although the outcrops of nepheline- and corundum-bearing rocks of this area have been described as being among the largest in the world, they are of minor extent, when compared with the other, less unusual rocks with which they are associated. Calculations by Chayes (1942), based on Adams and Barlow's maps, show that the alkaline rocks make up less than 6/10 of 1 per cent of all the rocks mapped, and only about 1 per cent of all the so-called igneous rocks in the region.

Structures

Most of the rocks which contain nepheline and corundum are gneissic. Layering and foliation are well developed, being brought out by parallel orientation of platy or prismatic mineral grains, alternation of layers of different composition and color, and alternation of layers of different grain size.

The structures of the gneisses which contain nepheline and corundum are entirely conformable with those of the associated rocks of the Grenville series. No evidence of intrusive relations whatsoever was found. The nepheline and corundum rocks grade, both along and across the strike, into more common members of the Grenville series, particularly dark gneisses. Gummer and Burr (1946) have noted concentrations of nepheline along fold axes. Locally, massive, coarsely crystalline rock-types occur.

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[1] The pegmatites and calcite veins have been described by Spence (1930) and Ellsworth (1932).

[2] General descriptions of various belts of nepheline and corundum rocks, and detailed reports of individual occurrences are included in the following references: Adams and Barlow (1910), Barlow (1915), Chayes (1942), Foye (1915), Gummer and Burr (1946), Keith (1939), Miller (1899), Osborne (1930), Satterly (1934, 1944), and Thomson (1943).

Composition

The rocks which carry or are associated with nepheline and corundum show a great range in composition. The area has been a happy-hunting-ground for the type of petrographer who takes delight in filling the pigeon holes of a classification of igneous rocks. This region furnished the type occurrences of monmouthite, dungannonite, craigmontite, congressite, and raglanite. In addition, the following names have been applied to rocks in the area; nepheline syenite, umptekite, plumasite, anorthosite, leuco-litchfieldite, leucomariupolite, syenodiorite, shonkinite, ijolite, foyaite, urtite, jacupirangite, and perknite. All of these names were applied to rocks which the writer finds difficult to accept as being of primary igneous origin.

The conspicuous compositional feature of the nepheline and corundum rocks is their high alumina content, as compared with the associated rocks. Burr and Gummer (1946) noted a range of 17 to 34 per cent of alumina in drill cores from the Bancroft area. A similar range was found in the York River area, where, in addition, there are several interbedded marbles which contain less than 4 per cent of alumina.

The chief minerals of the aluminous gneisses are nepheline, alkali feldspars, corundum, hornblende (in part hastingsite), biotite (lepidomelane), and magnetite. Calcite, apatite, and scapolite are common; zircon, tourmaline, and garnet are locally abundant. Sodalite, hackmanite, and cancrinite occur as relatively high temperature alteration products; natrolite, gieseckite, and hydronephelite as lower-temperature alteration products.

Mineral proportions, even in adjacent narrow layers, are extremely varied.

GENESIS OF THE NEPHELINE AND CORUNDUM ROCKS

Statement of Hypothesis

Many regions have been invaded and altered by granitic intrusives without development of nepheline or corundum. The writer considers that the key to the problem is in the composition of the Grenville series, in which marble and basic gneisses predominate, and highly siliceous rocks are rare. In common with others who have worked in the area, the writer believes that the nepheline and corundum gneisses were derived from pre-existing rocks of the Grenville series by reactions with hydrothermal emanations of magmatic origin.

Alteration of the Grenville Rocks by Magmatic Emanation

The granitic intrusives in the region cooled and crystallized in an entirely normal manner, giving off normal hydrothermal emanations, rich in silica, alumina, alkalies, and mineralizers, such as fluorine, chlorine, phosphorus, sulfur, and carbon dioxide. The early waves of emanations penetrated and reacted with the host rocks of the Grenville series.

In the dolomitic marble, diopside, tremolite, phlogopite, scapolite, forsterite, chondrodite, talc, and spinel were formed. The equations shown below indicate the trend of the reactions:

$$\underset{\text{dolomite}}{CaMg(CO_3)_2} + 2SiO_2 \rightarrow \underset{\text{diopside}}{CaMg(SiO_3)_2} + 2CO_2 \tag{1}$$

$$\underset{\text{dolomite}}{2CaMg(CO_3)_2} + SiO_2 \rightarrow \underset{\text{forsterite}}{Mg_2SiO_4} + \underset{\text{calcite}}{2CaCO_3} + 2CO_2 \tag{2}$$

The reaction forming tremolite would be essentially similar to that shown for diopside (equation 1) and the reactions forming the minerals of the chondrodite group would be quite similar to the one shown for forsterite (equation 2). Serpentine and talc may be derived from diopside, tremolite, forsterite, and chondrodite by hydration.

The emanations lost silica to the marble and gained carbon dioxide, a powerful fluxing agent. Carbonic acid solutions appear to show a greater affinity for soda than for potash, as is indicated by the effect of surface waters on outcrops of granitic pegmatites. Potash feldspar remains relatively fresh, while plagioclase becomes kaolinized.

It must be emphasized that the equations shown above, and those which follow, have been based on end products, as observed in the field, and represent merely the trends of alteration rather than the actual processes.

As the magmatic emanations penetrated amphibolite, reactions similar to the following may have taken place:

$$\underset{\text{labradorite}}{2NaCaAl_3Si_5O_{16}} + \underset{\text{alkali carbonate}}{2\left\{\begin{matrix} m\ Na_2CO_3 \\ nK_2CO_3 \end{matrix}\right\}} + 2SiO_2 \rightarrow \underset{\text{microperthite}}{4\left\{\begin{matrix} m\ NaAlSi_3O_8 \\ n\ KAlSi_3O_8 \end{matrix}\right\}} + \underset{\substack{\text{alkali}\\ \text{aluminates}}}{\left\{\begin{matrix} m\ Na_2Al_2O_4 \\ n\ K_2Al_2O_4 \end{matrix}\right\}} + \underset{\text{calcite}}{2CaCO_3}$$

Thus, alumina, in the form of alkali aluminates, would have been released to join with the emanations. Dark gneisses which have been partially converted to syenite-like composition are common throughout the area, and calcite, accompanied by other lime-rich minerals such as apatite, fluorite, scapolite, and sphene, occurs as veins and pockets in these rocks.

Formation of Nepheline

Through these various reactions with the host rocks, the emanations lost silica and potash and were thereby enriched in soda, alumina, and mineralizers. These emanations continued to traverse and permeate the overlying country rocks, penetrating by means of joints, faults, and pore spaces. But with their composition changed, these emanations would have induced reactions different from those induced earlier. In amphibolite, the calcic plagioclase would have been converted into nepheline and albite, as shown in the following equation:

$$\underset{\text{labradorite}}{\mathrm{NaCaAl_3Si_5O_{16}}}+\underset{\substack{\text{alkali}\\ \text{carbonate}}}{\left\{\begin{matrix} m\ \mathrm{Na_2CO_3} \\ n\ \mathrm{K_2CO_3}\end{matrix}\right\}}\rightarrow\underset{\text{nepheline}}{2(\mathrm{Na,\ K})\mathrm{AlSiO_4}}+\underset{\text{albite}}{\mathrm{NaAlSi_3O_8}}+\underset{\text{calcite}}{\mathrm{CaCO_3}}$$

If the plagioclase were less calcic, the following reaction might have obtained:

$$\underset{\text{albite}}{\mathrm{NaAlSi_3O_8}}+\underset{\substack{\text{alkali}\\ \text{aluminates}}}{\left\{\begin{matrix} m\ \mathrm{Na_2Al_2O_4} \\ n\ \mathrm{K_2Al_2O_4}\end{matrix}\right\}}\rightarrow\underset{\text{nepheline}}{3(\mathrm{Na,\ K})\mathrm{AlSiO_4}}$$

Where micaceous gneisses and schists were permeated by the emanations, the feldspars would have entered into reactions such as those shown above, while some of the mica might have been converted into nepheline in the following manner:

$$\underset{\text{muscovite}}{\mathrm{H_2(K,\ Na)Al_3Si_3O_{12}}}+\mathrm{Na_2CO_3}\rightarrow\underset{\text{nepheline}}{3(\mathrm{Na,\ K})\mathrm{AlSiO_4}}+\mathrm{H_2CO_3}$$

Aluminous biotites would be similarly affected.

Many more equations could be shown, but those above suffice to indicate the general trend of the reactions that might have been induced by the silica-poor emanations to form nepheline. It is probable that no one of these processes worked alone, but that several would have been in operation to form nepheline if that mineral were structurally stable under the prevailing thermodynamic conditions.

The primary composition of some of the beds or layers in the gneisses undoubtedly had a strong influence on the localization of the reactions. At a number of occurrences, bands which show repetition of outcrop, through folding, carry nepheline and/or corundum, while associated rocks in the same structures have been altered but lack those minerals.[3]

Keith's Plate 1 (1939), which shows the distribution of the various minerals in the Blue Mountain nepheline belt, might be interpreted as showing also the effect that folded beds of varied primary composition (and porosity?) would have had in the localization of reactions such as those noted above.

Massive, pegmatite-like bodies, composed of large crystals of nepheline, albite, and lepidomelane, are found within, and completely gradational into, the foliated nepheline rocks. Some of these bodies are localized along the axes of folds. Others occur along contacts between the gneisses and marble. The massive facies show replacement relations toward the marble, with well-developed nepheline and albite crystals penetrating outward into it.[4]

The concentration of mineralizer-rich emanations along the structurally favorable fold axes and additions of fresh carbon dioxide from the marble probably favored the growth of the large crystals, with concomitant destruction of the foliation of the host rocks.

Formation of Corundum

Nepheline, once formed, was not always stable. Later waves of emanations, following the same course as those which induced the formation of nepheline, would have lost less silica, since the host rocks would eventually have become saturated with it. Such emanations, as they entered the nepheline rocks, would introduce a more siliceous environment, favoring the stability of alkali feldspars rather than nepheline. The conversion of nepheline to alkali feldspars might have occurred simply by the addition of silica. However, in many cases, the reactions would have been of greater complexity, since free alumina was precipitated in the form of corundum, possibly in the following manner:

$$\underset{\text{nepheline}}{3(\mathrm{Na, K})\mathrm{AlSiO_4}} + \mathrm{CO_2} \rightarrow \underset{\text{microperthite}}{\begin{Bmatrix} m\ \mathrm{NaAlSi_3O_8} \\ n\ \mathrm{KAlSi_3O_8} \end{Bmatrix}} + \underset{\substack{\text{corun-}\\\text{dum}}}{\mathrm{Al_2O_3}} + \underset{\substack{\text{sod.}\\\text{carbonate}}}{\mathrm{Na_2CO_3}}$$

At a number of localities, nepheline-rich gneisses show partial alteration to rocks rich in alkali feldspars and corundum.[5]

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[3] Localities at which the repetition of bands of nepheline and corundum rocks is particularly well-shown include the Klondike Cuts at Craigmont (Raglan Twp. Con. XIX, Lot 11), and the area just north and west of Rosenthal (Radcliffe Twp. Con. I, Lots 28–31, Brudenell Twp. Con. IV and V, Lot 34).

[4] Examples of both of these types of occurrences are found in the vicinity of the Morrison Quarry on the York River, east of Bancroft (Dungannon Twp. Con. XIII, Lot 10).

[5] Such localities include Welsh's mine (Monteagle Twp. Con. I & II, Lots 2 & 3), the

The formation of corundum was not always dependent on the presence of nepheline. At many localities, the calcic feldspars of the dark gneisses appear to have been attacked directly, to form alkali feldspars and corundum,[6] possibly by a reaction like the following:

$$\underset{\text{labradorite}}{3NaCaAl_3Si_5O_{16}} + 2CO_2 + Na_2CO_3 \rightarrow \underset{\text{corundum}}{2Al_2O_3} + \underset{\text{albite}}{5NaAlSi_3O_8} + \underset{\text{calcite}}{3CaCO_3}$$

The writer has examined a number of occurrences of this type, some of them quite extensive, where syenitoid, corundum-rich gneisses grade into the more common, corundum-free dark gneisses.[7] Calcite and lime-rich scapolite are common at many of these occurrences.

In most of these occurrences, however, the reactions which formed corundum could not be as simple as that shown above, since some of the hornblende and biotite of the gneisses was altered to form magnetite, and the alumina originally present in these minerals may also have been converted into corundum.

Throughout the area, the dark minerals, as well as the light minerals of the gneisses were affected. As alteration progressed, hornblende gave way to biotite, and biotite to magnetite. These changes were quite localized, and the dark minerals vary along the strike, as well as from layer to layer across the strike.

In some cases, the alteration of the basic gneisses to syenite-like varieties apparently involved little change in total iron content. Many of the nepheline-bearing gneisses, particularly those of the York River belt, contain large amounts of iron-rich amphibole, biotite, pyroxene, and garnet, in addition to magnetite. In most instances, however, part of the iron appears to have been removed by the emanations which were responsible for the alteration. The iron which is present in the euhedral magnetite crystals that are associated with calcite veins throughout the

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type dungannonite occurrence (Dungannon Twp. Con. XIII & XIV, Lots 12 & 13), Egan Chute on the York River (Dungannon Twp. Con. XII, Lot 12), the Lillie Robertson Hill in the Bancroft area (Dungannon Twp. Con. XIII, Lot. 26), the Klondike cuts at Craigmont (Raglan Twp. Con. XIX, Lot 2), the adit in the Craigmont main workings (Raglan Twp. Con. XVIII, Lot. 13), several occurrences along the township road a short distance north of Rosenthal (Brudenell Twp. Con. V, Lot 34 and Radcliffe Twp. Con. IV, Lot 31), and one of Jewelville occurrences (Raglan Twp. Con. XIX, Lot 26).

[6] Tomlinson (1939) suggested, with corroborating evidence from a Pennsylvania occurrence, that alumina might be released and precipitated locally, as corundum, upon conversion of calcic plagioclase to alkali feldspar.

[7] Occurrences of this type include the main workings at Craigmont (Raglan Twp. Con. XVIII–XIX, Lots 3–4), several deposits northwest of Rosenthal (Radcliffe Twp. Con. I, Lots 28–31), three of the Jewelville workings (Raglan Twp. Con. XIX, Lots 25–26), a prospect north of the Grady Lake cuts in the Burgess Mines Area (Carlow Twp. Con. XVI, Lot 15), and an outcrop west of Palmer Rapids (Raglan Twp. Con. XV, Lot 22).

area, and the iron which is present in the magnetite replacement bodies in the marble,[8] may have been derived from the ferro-magnesian minerals of the Grenville gneisses.

In the altered gneisses, corundum was never observed in layers containing hornblende, rarely observed in layers containing biotite, and generally found in layers containing magnetite.

Crystallization of the major portions of the granitic intrusives proceeded in the usual manner, with development of large amounts of normal pegmatitic material which invaded the region in the form of dikes and sills. Where nepheline-bearing gneisses were cut by bodies of granitic pegmatite, syenite-like contact zones were developed in which nepheline was destroyed and alkali feldspars and corundum were formed. The Mt. St. Patrick nepheline belt contains excellent examples of this type of contact alteration. There, gneisses composed of nepheline, albite, and biotite are cut by large dikes of coarsely crystalline granitic pegmatite. In contact zones several feet wide, nepheline and biotite are absent and microperthite, magnetite, corundum, and quartz are present.

Nepheline and quartz were never found in close association. However, corundum and quartz are not only not mutually exclusive, but, throughout the whole area, quartz is commonly associated with corundum.

While tracing belts of the altered dark gneisses, the writer found many of these to be free of corundum except in those portions immediately adjacent to granitic pegmatites, and at many localities, the corundum was in close association with masses of quartz. Many occurrences of this type were mapped, including the most extensive corundum deposits in southeastern Ontario.[9]

An occurrence where the influence of granitic pegmatites is well shown is just north of the type dungannonite locality of Adams and Barlow (1910), along the York River, close to the common corners of Concession XIII and XIV and lots 12 and 13 in Dungannon Twp. There, corundum is found in altered dark gneiss, but only where such rock is in immediate contact with the granitic pegmatite that makes up the bulk of the ridge. In many places, the altered rock is broken up and small fragments "float" in the pegmatite. These inclusions carry corundum crystals in considerable quantity, concentrated along foliation planes. It is notable that no minerals of the andalusite-sillimanite-kyanite group were observed at any of the corundum occurrences.

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[8] Such deposits include the Bessemer, Childs and Rankin deposits, about 10 miles east of Bancroft. These deposits are described by Thomson (1943).

[9] These occurrences include portions of the main workings at Craigmont (Raglan Twp. Con. XVIII–XIX, Lots 3–4), the main workings at Burgess Mines and the Buck Creek and Grady Lake Cuts in the Burgess Mines Area (Carlow Twp. Con. XIII to XVI, Lots 11 to 16), outcrops in the southern portion of the Mt. St. Patrick nepheline belt (Brougham Twp. Con. XII and XIII, Lots 11 and 12), one of the Jewelville strippings (Raglan Twp. Con. XIX, Lot 27), a ledge in the area between the York and Madawaska Rivers (Raglan Twp. Con. XVII, Lot 17), two workings at Rosenthal (Brudenell Twp. Con. IV, Lot 34), outcrops just north of the Wolfe nepheline belt (Lyndoch Twp. Con. XV, Lot 13), a deposit near the eastern end of Lake Charlotte (Brudenell Twp. Probably Con. VII, Lot 20), an outcrop just west of the Brudenell-Letterkenny Road (Brudenell Twp. Con. V, Lot 24), the cuts of the National Corundum Co. (Monteagle Twp. Con. I, Lot 13), outcrops just north of the type dungannonite occurrence of Adams and Barlow, along the York River (Dungannon Twp. Con. XIII and XIV, Lot 12 and 13), and outcrops along the road between Kinmount and Miner's Bay (Lutterworth Twp. along the boundary between Con. III and IV, Lot 12).

In proximity to the granitic pegmatites, many of the gneisses have been recrystallized, with considerable increase in grain size, and redistribution of constituents. Since the foliation of a gneiss is dependent on the orientation and distribution of its component small grains, recrystallization of these grains into large crystals would tend to destroy the foliation. It is possible that such obliteration of foliation in the dark gneisses led earlier workers in the region to conclude that the coarse-grained, corundum-bearing rocks were intrusives (the so-called corundum pegmatites). However, close study at many localities reveals the gradational and nonintrusive nature of the coarse-grained corundum-bearing facies.

Later Alterations

As the intrusives cooled and the temperature gradients of the surrounding rocks dropped, mineral stabilities were further affected, and new minerals were developed at the expense of those formed earlier. Sodalite, hackmanite, and cancrinite occur widely throughout the area as replacements of nepheline. For the most part, these minerals were probably formed by emanations directly related to those which formed the nepheline itself. At some localities, however, particularly in the Bancroft area, sodalite and cancrinite have been developed in nepheline-bearing gneisses which were intruded by syenite dikes. The syenite dikes were probably responsible for the development of the veins in the Bancroft area, in which large, well-formed crystals of nepheline, albite, and lepidomelane project outward from the wall rocks into masses of coarsely crystalline calcite. These veins fill wide tension joints, which transect the foliation of nepheline-bearing gneisses and are thus later in origin than the minerals of the gneiss. Emanations from the syenite dikes may have acted as fluxing agents, causing partial solution and recrystallization of the wall rocks along available channelways.

It is possible that the syenite of these intrusives may have been developed by localized reactions between granitic magma and silica-poor country rocks, particularly in those portions of the magma chambers which had been isolated from the main bodies by accumulations of large inclusions of country rocks. In many places throughout the region, it is difficult to determine whether an outcrop is a part of a granitic stock that is badly choked with inclusions, or is a portion of the country rock that has been transected by dikes and stringers of igneous rocks. The country rocks in such occurrences have been heavily charged with granitic or syenitic magma through lit-par-lit injection.

The activity of juvenile emanations is indicated throughout the area by the presence in the nepheline rocks of minerals which are generally considered to be of primary origin. Crystals of cyrtolite found in the massive, coarsely crystalline bodies of nepheline rock along the York River are indistinguishable from those which are contained in the granitic pegmatites of the famous MacDonald Mine, at Hybla, several miles to the north (Spence, 1930, Ellsworth, 1932). Galena, in amoeboid masses, occurs in the nepheline rocks at the quarries of the American Nepheline Company on Blue Mountain in Lake Township, and traces were found at Egan Chute on the York River, in Dungannon Township. Zircon, arsenopyrite, pyrrhotite, tourmaline, allanite, and molybdenite were observed in nepheline rocks at various places.

In almost all of the occurrences of nepheline-bearing rocks, a considerable amount of the nepheline has been altered to pink or green clay-like material, particularly along the joints. In the massive, coarsely crystalline facies, individual crystals of nepheline show a series of alteration products. Each large crystal has a core of fresh translucent, gray nepheline which is surrounded by a zone of opaque, white cancrinite. The cancrinite grades into a zone of fine-grained pink material, and the latter is surrounded by a rim of fine-grained green material.[10] Whole joint blocks of the finer-grained nepheline rocks show similar gradations. In each block, the small nepheline grains of the interior are fresh, while those nearer to the joints are colored white, pink or green, depending on their respective distance from the joint-surfaces.[11]

The pink material has been called hydronephelite by most of the workers in the region and is believed to be a fine-grained mixture of natrolite and muscovite. The green material has been called gieseckite, and is considered to be composed chiefly of fine-grained muscovite. In addition to these fine-grained varieties, natrolite and muscovite are both common in more readily recognizable form. Natrolite, as colorless acicular crystals, lines joint fissures and vugs in the nepheline-bearing gneisses of the Bancroft and York River areas. Locally, small analcite crystals are associated with the natrolite. In the colorful specimens from the Princess Sodalite Quarry in the Bancroft area (Dungannon Twp. Con. XIV, Lot 25), pink natrolite occurs in the form of radial aggregates replacing sodalite along joint fissures. Muscovite, in large plates, is common in the coarsely crystalline nepheline rocks of the York River area. An interesting occurrence of muscovite was found just east of the Morrison Quarry (Dungannon Twp. Con. XIII, Lot 10). There, large, well-formed, sharp-edged crystals of nepheline and albite had developed within the Grenville marble. The nepheline crystals were later completely altered to twisted aggregates of light-colored mica, but retained their original outward form. In view of the occurrence, it was thought that this mica might be paragonite, and a specimen was sent from the field to Dr. Waldemar T. Schaller, who was then studying paragonite. Dr. Schaller's tests proved the mica to be muscovite.[12]

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[10] Alteration of this type is well shown by the large crystals of nepheline which occur in the massive facies of the nepheline rocks that crop out in the York River area.

[11] This type of alteration is well shown at the quarries of the American Nepheline Company on Blue Mountain, Lake Twp.

Hydrothermal emanations, of lower temperature and possibly of higher silica content than those which formed the nepheline, are considered to have been responsible for the alteration of nepheline to natrolite, muscovite, hydronephelite and gieseckite. The alteration products are generally related to joints and other openings of comparatively late origin, which indicate an environment of lower temperature. The trend of reactions which might account for such alteration of the nepheline might be:

$$\underset{\text{nepheline}}{2NaAlSiO_4}+SiO_2+2H_2O\rightarrow\underset{\text{natrolite}}{Na_2Al_2Si_3O_{10}\cdot 2H_2O}$$

(The above equation was simplified by the omission of potassium from the nepheline)

$$\underset{\text{nepheline}}{3(Na, K)AlSiO_4}+H_2CO_3\rightarrow\underset{\text{muscovite}}{H_2KAl_3Si_3O_{12}}+Na_2CO_3$$

In most of the occurrences, corundum crystals are rimmed by muscovite. In some cases, the muscovite is fine-grained, in others large plates of muscovite surround and partially replace the corundum. These rims were probably formed under conditions of mineral instability due to cooling and may represent reactions between corundum and enveloping fluids, or reactions between corundum and adjacent feldspar, with the aid of such fluids.

Age Relations

Recent literature contains a considerable amount of discussion on the relative ages of the granitic intrusives and the nepheline-bearing gneisses. There is no justification for tying the genesis of any particular belt of nepheline-bearing rock to the nearest large granitic intrusive, unless this relationship is indicated by field evidence. Intrusive activity was undoubtedly of long duration in the region and it is quite possible that the nearest outcropping stock was not the source of the emanations responsible for the major alteration of the dark gneisses. At many of the nepheline occurrences there is evidence indicating that nearby granitic stocks are of later origin than the nepheline rocks. There are numerous zones around the periphery of the Blue Mountain nepheline belt where syenite-like rocks which contain corundum, but no nepheline, appear to have been developed at the expense of the nepheline-bearing rocks. These occurrences, together with N. B. Keevil's determination of the ages of various rocks in the region by helium, radium, and thorium ratios (Keith, 1939), indicate that the emplacement of the nearby Methuen Batholith was later than the formation of the nepheline in the Blue Mountain belt.

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[12] Personal communication.

Nor is there any reason to believe that all of the nepheline occurrences are of contemporaneous origin and that all of the corundum occurrences are contemporaneous. Host rocks of favorable composition were common throughout the region, thus the major variable was the emplacement of igneous bodies from which emanations would have been released. Since there was a long period during which such bodies might have been intruded, there must also have been a long period during which nepheline and corundum could have been formed. As yet, it is known only that locally, throughout the region, the necessary conditions were met and nepheline or corundum was developed. It is certain that more occurrences reflecting those favorable conditions will be discovered when the whole region is mapped in greater detail. Numerous occurrences of nepheline and corundum were discovered by the writer and others working in the area in recent years, and without doubt, many more, possibly some of considerable extent, remain to be recognized.

SUMMARY

Field evidence appears to indicate that most of the nepheline and corundum rocks of southeastern Ontario were derived from pre-existing dark gneisses of the Grenville series by reaction with hydrothermal emanations of magmatic origin. These emanations were released during the cooling and crystallization of normal granitic masses and carried the usual complement of silica, alumina, alkalies, and mineralizers. In traversing the silica-poor rocks of the Grenville series, the emanations reacted with these rocks, developing silicates in the dolomitic marble and altering the basic dark gneisses to syenite-like varieties. In these reactions, the emanations lost some of their silica, but gained carbon dioxide. The emanations, thus enriched in alumina and the alkalies, continued to traverse and react with the dark gneisses, converting calcic feldspar to alkali feldspars and nepheline. Later emanations from the same sources, following the same routes, lost less silica to the host rocks, and reacted with some of the nepheline formed by the earlier emanations, converting it to alkali feldspars and corundum. Where the more siliceous emanations and the normal granitic pegmatites invaded the dark gneisses, the calcic feldspar of the latter was converted to alkali feldspars and corundum, and some of the ferromagnesian minerals were converted to magnetite and corundum. Most of the nepheline and corundum rocks are gneisses and their structures are conformable with those of the surrounding, less unusual gneisses of the Grenville series. Locally, the gneissic structures have been destroyed by recrystallization, with considerable coarsening of grain size. Pre-existing variations in composition, structure and texture of the gneisses influenced the localization of the nepheline and corundum. Locally, nepheline was partially altered to cancrinite, sodalite, and hackmanite by additions of the required mineralizers, some of which were released from syenite intrusives. As igneous activity declined, some of the nepheline and associated minerals were partially altered to natrolite, muscovite, hydronephelite, and gieseckite, and much of the corundum was partially altered to muscovite.

It will be noted that in this presentation of a possible genesis for the nepheline and corundum-bearing gneisses, the writer has called upon no unusual, large scale processes such as the wholesale down-stoping and assimilation of country rocks, the fractional crystallization and settling away of peculiar portions of the magma, a perfectly-timed diastrophism or fortuitous filter-pressing. Instead, this working hypothesis has been based entirely on observations of exposures in the field—intrusive granitic stocks, highly silicated marble, altered gneisses, large calcite veins, concordant and non-intrusive structures, minerals which now exist, and processes which can be recreated at various stages, from the frozen products as they occur in the outcrops, locality by locality. None of these occurrences is unique. Instead, gradations to a lower or higher degree of alteration can be found, either at the same locality or at others within the area.

The genesis of any one of the occurrences, taken singly, might be difficult to interpret, but if that occurrence be considered as one unit or phase, among hundreds of related occurrences showing the whole range of alterations, its position in the general scheme might soon be determined.

Bibliography

Adams, F. D., and Barlow, A. E. (1910), Geology of the Haliburton and Bancroft Areas: *Geol. Surv. Can. Mem.* **6**.

Barlow, A. D. (1915), Corundum, its occurrence, distribution, exploitation, and uses: *Geol. Surv. Can., Mem.* **57.**

Bowen, N. L. (1928), Evolution of the Igneous Rocks, Princeton Univ. Press.

Chayes, Felix (1942), Alkaline and carbonate intrusives near Bancroft, Ontario: *Geol. Soc. Am., Bull.*, **53,** 449–510.

——— (1945), Recent studies of Haliburton-Bancroft alkaline rocks: A Discussion. *Jour. Geol.*, **LIII,** No. 6, 405–408.

Daly, R. A. (1933), Igneous Rocks and the Depths of the Earth, McGraw-Hill Book Co., Inc., New York.

Ellsworth, H. V. (1932), Rare-element minerals of Canada: *Geol. Surv. Can., Econ. Geol. Series* No. **11.**

Fairbairn, H. W. (1943), Packing in ionic minerals: *Geol. Soc. Am., Bull.*, **54,** 1305–1374.

Foye, W. J. (1915), Nepheline syenites of Haliburton County, Ontario: *Am. Jour. Sci.*, **40,** 424.

Gillson, J. L. (1928), The origin of alkaline rocks: *Jour. Geol.*, **36,** 473.

Goudge, M. F. (1938), Limestones of Canada, Part IV, Ontario: *Can. Dept. Mines and Resources*, No. **781.**

Gummer, W. K., and Burr, S. V., (1943), The nephelinized paragneisses of the Bancroft Region, Ontario: *Science*, **97,** No. 2517, 286–287.

——— (1946), Nephelinized paragneisses in the Bancroft Area, Ontario: *Jour. Geol.*, **LIV,** No. 3, 137–168.

Keevil, N. B. (1938), Application of the helium method to granites: *Roy Soc. Can., Tr.*, **32,** p. 123.

Keith, M. L. (1939), Petrology of the alkaline intrusives at Blue Mountain, Ontario: *Geol. Soc. Am., Bull.*, **50,** 1795–1826.

Miller, W. G. (1899), Notes on the corundum-bearing rocks of Eastern Ontario: *Am. Geol.*, **XXIV,** 276–282.

Osborne, F. F. (1930), The nepheline gneiss complex near Egan Chute, Dungannon Township: *Am. Jour. Sci.*, 5th Series, **20,** 33.

Satterly, J. (1943), Mineral occurrences in the Haliburton Area: *Ont. Dept. Mines*, **52***nd Ann. Rept.*, **LII,** Part II.

——— (1944), Mineral occurrences in the Renfrew Area: *Ont. Dept. Mines*, **53***rd Ann. Rept.*, **LIII,** Part III.

Shand, S. J. (1927), Eruptive Rocks, Murby & Co., London.

——— (1945), The present status of Daly's hypothesis of the alkaline rocks: *Am. Jour. Sci.*, **CCXLIIIA,** Daly Volume, 495–507.

——— (1946), Discussion: The origin of nepheline rocks in Ontario: *Jour. Geol.*, **LIV,** No. 6.

Smyth, C. H. (1913), The chemical composition of alkaline rocks and its significance as to their origin: *Am. Jour. Sci.*, **36,** 40.

——— (1927), The origin of alkaline rocks: *Jour. Geol.*, **36,** 473.

Spence, H. S. (1930), Pegmatite minerals of Ontario and Quebec: *Am. Mineral.*, **15,** Nos. 9–10, 430–450; 474–496.

Thomson, Jas. E. (1943), Mineral occurrences in North Hastings Area: *Ont. Bur. Mines*, **52***nd Ann. Rept.*, **LII,** Part III.

Tomlinson, W. H. (1939), Corundum in a dike at Glenn Riddle, Pennsylvania: *Am. Mineral.*, **24,** No. 5, p. 339.

SCREW AXES OF SYMMETRY AND THEIR SYMBOLS*

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ABSTRACT

The usefulness of Mauguin symbolism is demonstrated by its adaptation in slightly modified form for the characterization of screw axes. The symbols of all screws isomorphous with any given rotary axis and the geometrical properties essential for their visualization can be found by simple arithmetical means. The otherwise difficult subject of non-crystallographic chain symmetry groups is thus greatly simplified.

Screw axes are elements of symmetry of chain groups and space groups (the digonal screw also occurs in net groups). They are the controlling elements of operations of translatory rotation. In space groups we only have the fifteen crystallographic screw axes with Mauguin symbols 2, 2_1, 3, 3_1, 3_2, 4, 4_1, 4_2, 4_3, 6, 6_1, 6_2, 6_3, 6_4, 6_5. In chain groups, however, where translation is admitted in only one dimension, we have an infinite number of non-crystallographic screws, some of which may conceivably be found in chain molecules, which do not crystallize to nets or lattices. The principle of Mauguin symbolism can be adapted to characterize screws in general and combinations of screw axes with rotary axes in the same line.

A *pure* screw axis is one which is not combined with a rotary axis in the same line. The symbol of a pure screw is given in the Mauguin form p_q. We interpret the symbol as follows: p operations (the single operation is rotation around the axis through the angle α and translation through the distance τ/p parallel to the axis) result in q complete revolutions around the axis and a total translation τ, which is the period of identity. Therefore $\alpha = q \cdot 360°/p$ is the rotational component of the screw and τ/p is the translational component. In consequence it must be stipulated that p and q be integers without common divisor. Also $p > q$, as otherwise $\alpha > 360°$. When $p = q$, $\alpha = 360°$, so that 1_1 can be used as a symbol for periodicity along the screw axis.

Every screw can be interpreted as a *right* or a *left* screw. If the right screw has the rotational component α, the corresponding left screw has the rotational component $(360° - \alpha)$. If we imagine a screw motion towards us along an axis, we call the axis a right screw when the rotation is counter clockwise through the smallest angle $\alpha < 180°$ which will produce coverage of equivalent points. When $\alpha = 180°$, the screw is both right and left and can be called *neutral.*

p_q is a right screw when $p > 2q$
p_q is a left screw when $p < 2q$
2_1 is the only neutral pure screw.

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Two screws p_q and $p_{(p-q)}$ can be enantiomorphous, one being the mirror picture of the other. One is right and the other left, for if p_q has the rotational component α, then $p_{(p-q)}$ has the component $360° - \alpha = -\alpha$, so $p_q = -p_{(p-q)} = p_{(q-p)}$. The use of negative symbols is usually unnecessary, the above relation being given mainly to show that when calculation yields values with $q > p$, we can subtract p from q repeatedly until $q < p$.

COMBINATION OF AXES OF ROTATION AND SCREW AXES

We combine n (rotary axis) and p_q in one line and write n, p_q. This combination produces further elements $p'_{q'}$ in the same line. If $\sigma = 360°/n$ is the smallest angle of rotation of n, and $\alpha = q \cdot 360°/p$ is the smallest rotational component of p_q, then the rotational component of the implied axes $p'_{q'}$ is $(\alpha + a\sigma)$, where a is any integer.

$$p'/q' = 360°/(\alpha + a\sigma) = np/(nq + ap)$$

$$n,\ p_q = n,\ np_{(nq+ap)} \tag{1}$$

The translational component is n/p, where p has its maximum value. In computing the different symbols for the same axis by means of the above equation, the procedure is to make $np > (nq + ap)$ by subtraction of np from the latter term when necessary, and then to treat $np_{(nq+ap)}$ as a fraction and reduce it to its lowest form.

The calculated different expressions for a given combination of rotary and screw axes yield significant information on the geometrical properties of screws. For instance, the Mauguin screw 6_3 is written more significantly as $3, 6_1$, which shows that it is a combination of a trigonal rotary axis and a right hexagonal screw. Use of equation (1) reveals that $3, 6_5$ and $3, 2_1$ are synonymous expressions and we see that the screw is neutral.

ISOMORPHOUS AXES

All axes which reduce to p on suppression of translation are said to be *isomorphous* with the class (point group) p. Isomorphous axes have the following properties in common: equivalent points lie on equally spaced parallel lines on a cylinder surface. There are p such lines, all of which must carry equivalent points. All multiples of $\sigma = 360°/p$ must therefore result from the symmetry operation.

This is realized for all axes p_q (p and q have no common divisor and $p > q$). Thus we have, for instance, four pure screw axes isomorphous with the point group 5. They are $5_1, 5_2, 5_3, 5_4$, with the angular components 72°, 144°, 216°(−144°), and 288°(−72°), respectively, as computed from $\alpha = q \cdot 360°/p$. The first two are right screws and the others left. The fifth axis isomorphous with 5 is $5, 1_1$ which is the periodic repetition of 5. Thus when p is prime we can immediately write the symbols of all the isomorphous axes $p, 1_1, p_1, p_2, - p_{(p-2)}, p_{(p-1)}$.

When p is not prime, the procedure is to write down the symbols p_q where q is all integers from 1 to p. The pure screws are obtained by picking out the symbols with numbers without common divisor. When p_q has a common divisor n, an axis n, 1_1 is indicated and we write n, np_q. This symbol stands for a combination of n, 1_1 with np_q (which is treated as a fraction and reduced to its lowest form). When $p=q$ we get p, p_1 which is equal to p, 1_1.

We thus have p axes isomorphous with p, as q assumes all integral values from 1 to p. When p is even, we have a neutral screw $p/2$, p_1. For instance, $p_q=4_2$, then the axis is 2, 4_1, a right screw. The symbol of the substitutable left screw 2, 4_3 is obtained from equation (1).

We now have a simple method for determining and symbolizing all screws isomorphous with any given rotary axis, and of ascertaining their geometrical properties. The table shows the symbols of the screws isomorphous with the axes 2 to 12.

SPECIAL CASES

In screw axes, the rotational component can be an irrational fraction of 360°. The period of identity then becomes infinitely large, although the translational component of the screw is finite. Translation is not a sub-group of irrational screws. The symbol of this class of screws is r_1, where r is an irrational number. There is an infinite number of screws r_1 and n, r_1, which are isomorphous with rotary axes (as yet unsymbolized), which themselves are perhaps only sub-groups of the axis ∞. Here the symbol ∞ designates a rotary axis, the angle of rotation being a free variable, i.e. assuming all angular values. Thus the axis ∞ establishes equivalence of *all* the points of a circle. It would seem that although the equivalent points due to an irrational screw r_1 form a dense circle on supression of the translational component, this circle does not have the symmetry ∞, because an infinite number of points, corresponding to rational angles, are missing. This problem awaits investigation.

Finally there are the helices, continuous screws, all the points of which are equivalent. The symbols are ∞_1 and n, ∞_1. We can distinguish between right and left helices by use of a negative symbol for the left one.

The group ∞, ∞_1 is equal to the group $\infty/m\ m$ (with free variable translation), representing the symmetry of a cylinder surface, all the points of which are equivalent.

COMBINATION OF SCREW AXES WITH OTHER ELEMENTS OF SYMMETRY IN CHAIN GROUPS

All screw axes n, p_q (also n, r_1 and n, ∞_1) can be combined with digonal axes normal to them, to form chain groups n, p_q2 (n, r_12 and n, ∞_1 2),

Symbols of Screw Axes Isomorphous with Rotary Axes 2 to 12
Computed from: n, $p_q = n$, $np_{nq} + ap$

Rotary Axis	Pure Right Screws	Pure Left Screws	Combination of Axes of Rotation and Right Screws	Combination of Axes of Rotation and Left Screws	Neutral Screws	
2					$2, 1_1$	2_1
3	3_1	3_2			$3, 1_1$	
4	4_1	4_3			$4, 1_1$	$2, 4_1 = 2, 4_3$
5	5_1 5_2	5_3 5_4			$5, 1_1$	
6	6_1	6_5	$2, 6_1 = 2, 3_2$	$2, 3_1 = 2, 6_5$	$6, 1_1$	$3, 6_1 = 3, 2_1 = 3, 6_5$
7	7_1 7_2 7_3	7_4 7_5 7_6			$7, 1_1$	
8	8_1 8_3	8_5 8_7	$2, 8_1 = 2, 8_5$	$2, 8_3 = 2, 8_7$	$8, 1_1$	$4, 8_1 = 4, 8_3 = 4, 8_5 = 4, 8_7$
9	9_1 9_2 9_4	9_5 9_7 9_8	$3, 9_1 = 3, 9_4 = 3, 9_7$	$3, 9_2 = 3, 9_5 = 3, 9_8$	$9, 1_1$	
10	10_1 10_3	10_7 10_9	$2, 10_1 = 2, 5_3$ $2, 10_3 = 2, 5_4$	$2, 5_1 = 2, 10_7$ $2, 5_2 = 2, 10_9$	$10, 1_1$	$5, 10_1 = 5, 10_3 = 5, 2_1 = 5, 10_7 = 5, 10_9$
11	11_1 11_2 11_3 11_4 11_5	11_6 11_7 11_8 11_9 11_{10}			$11, 1_1$	
			$2, 12_1 = 2, 12_7$	$2, 12_5 = 2, 12_{11}$	$12, 1_1$	
12	12_1 12_5	12_7 12_{11}	$3, 12_1 = 3, 12_5 = 3, 4_3$	$3, 4_1 = 3, 12_7 = 3, 12_{11}$	$6, 12_1 = 6, 4_1 = 6, 12_5 = 6, 12_7 = 6, 4_3 = 6, 12_{11}$	
			$4, 12_1 = 4, 3_1 = 4, 12_7 = 4, 6_5$	$4, 6_1 = 4, 12_5 = 4, 3_2 = 4, 12_{11}$		

but combination with planes normal to or containing the screw axis, or with centers of symmetry, is only possible for neutral screws, i.e. $n, 1_1$ or $n, p_q = n, p_{(p-q)}$.

SUB-GROUPS

Sub-groups are groups of operations which cover only a fraction of the equivalent points of the whole group. Thus translation 1_1 is a sub-group of all screws excepting irrational ones.

A pure screw p_q has sub-groups $p_{q(1+a)}$ where a assumes all integral values from 1 to $p-2$, translational component $(1+a)/p$. The addition of translation will yield the equivalent points of the operation p_q which have been skipped by the operation $p_{q(1+a)}$, but only when p and $q\ (1+a)$ have no common divisor. The pure left screw 6_5, for instance, has the sub-groups 1_1, 6_1, 2_1, 3_1, and 3_2. In addition to the sub-groups of its screw n, p_q of course has sub-groups $n, 1_1$ and $d, 1_1$ where d is a divisor of n. Further sub-groups are $n, p_{q(1+a)}$, $d, p_{(1+a)}$, and d, p_q.

Finally, all pure screws, rational and irrational, are sub-groups of the helix.

NOTES AND NEWS

TALC IN THE SALINES OF THE POTASH FIELD NEAR CARLSBAD, EDDY COUNTY, NEW MEXICO*

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Very thin micaceous flakes of a then unidentified mineral, now known to be talc, were first noted about 20 years ago as one of the constituents of the water-insoluble residues from some of the potash cores obtained by drilling near Carlsbad, Eddy County, New Mexico. The residues consisted largely of iron-stained clay, with sand grains and other materials. The flakes first floated to the surface of the water used in dissolving the salines of the cores and sank to the bottom on standing overnight.

A few years later when the cores of Government well drill tests Nos. 20, 21, and 22 had to be disposed of, for lack of storage space, they were dissolved in water and the insoluble residues saved. All three cores contained talc, most abundantly in the core from test No. 22. It was floated off and saved. A total weight of about 5 grams was so recovered.

The location of these three test holes is as follows:

Test No. 20. Sec. 1, T.23S., R.32E., Lea County, N. Mex.
Test No. 21. Sec. 11, T.21S., R.34E., Lea County, N. Mex.
Test No. 22. Sec. 26, T.23S., R.30E., Eddy County, N. Mex.

Similar flakes, in smaller quantities, were noted from time to time in other cores from Eddy and Lea Counties.

The talc occurred in the cleavage cracks of halite, of sylvite, and between halite and sylvite. In places it formed a rectangular boxwork with included halite, the walls easily breaking into separate transparent flakes with inclusions of reddish clay and of iron oxide. The flakes are so thin that it was difficult to obtain any appreciable weight of them. They were best collected electrostatically by using a small charged camel's hair brush on bright sunny days. About a tenth of a gram was at first so concentrated. Chemical tests indicated a hydrous magnesium silicate, though a definite test for boron was obtained. The boron is probably present as inclusions of lueneburgite.[1]

The largest of the single flakes of talc are about 7 millimeters across and exceedingly thin. Feebly coherent aggregates of flakes reach a maximum size of about a centimeter. The thickest flake measured is about a hundreth of a millimeter thick. They are colorless and transparent but contain various impurities so that in bulk the sample has a reddish-brown color due to iron oxide. Most of the flakes have an irregular outline though a few tend toward a six-sided shape.

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[1] Schaller, W. T., and Henderson, E. P., Mineralogy of drill cores from the potash field of New Mexico and Texas: *U. S. Geol. Survey, Bull.*, **833**, 47–48 (1932).

Mr. Joseph M. Axelrod found that the purest material gave an x-ray diffraction pattern identical with that of talc. Optically, the talc from New Mexico was seen to be nearly uniaxial, negative, with β and γ values very close to 1.580. This value is slightly lower than the 1.589 given by Larsen-Berman, but a range of 1.575 to 1.585 is recorded.[2] There seem to be very few determinations of the indices of refraction for talc recorded in the literature.

About 0.3 gram of the flakes were finally collected for chemical analysis to leave no doubt as to their composition. The analyzed flakes contained only a small quantity of impurities.

Analysis of talc from test No. 22, Eddy County, New Mexico

SiO_2	59.5
MgO	29.4
R_2O_3	1.8
K_2O	1.7
Ignition	6.6
B_2O_3	Present
	99.0

The R_2O_3 is largely impure iron oxide. No test for sulfate was obtained. B_2O_3 was not determined but is present, probably as inclusions of lueneburgite.

The analysis yields the ratios of $SiO_2:MgO:H_2O = 4.00:2.95:1.47$. The value for ignition includes H_2O at 110° (not separately determined) and possibly other volatiles, so that the 6.57 per cent ignition loss does not necessarily indicate a high-water talc.

A re-examination, by W. T. Schaller, of the thin section from a part of the core from the Ballard well (Eddy County, Sec. 18, T. 21 S., R. 30 E.), represented in part by Plate 23*C* of U. S. Geological Survey, Bulletin 833, shows that the supposed "polyhalite fibers" in the rectangular cleavage cracks of halite are probably thin flakes of talc standing on edge. The typical boxwork structure already mentioned for the talc is well shown in the upper portion of the illustration. Similarly, the supposed "minute areas of polyhalite" shown in Plate 23*B*, when re-examined, prove to be not polyhalite but six-sided crystals of an unidentified mineral with indices of refraction lower than the index of halite (1.544) mixed with a few flakes (indices higher than 1.544) of what is probably talc.

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[2] Foshag, W. F.. and Wherry, E. T., Notes on the composition of talc: *Am. Mineral.*, **7**, 168 (1922).

This type of occurrence of talc, with sodium and potassium chlorides of sedimentary deposits, does not seem to have been noted before. Its occurrence in the cleavages of halite and sylvite (Plate *23C* of Bulletin 833) would indicate that its formation in the salines is secondary and later than their deposition. The talc has been definitely recognized in three cores from New Mexico and probably is present in several others; it seems to be rather widespread in this field.

NATURAL EX-SOLUTION INTERGROWTHS OF MAGNETITE AND HEMATITE

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The object of this note is to record three natural occurrences of ex-solution intergrowths of magnetite and hematite. Investigation of the equilibrium relationships of Fe_3O_4, Fe_2O_3 and oxygen[1] has shown that at high temperatures hematite and magnetite form a partial solid solution, which unmixes on slow cooling to form an intergrowth of hematite lamellae in the (111) directions of the magnetite, the orientation being explicable in terms of shared O-planes (the (0001) O-planes of the hematite and the (111) O-planes of the magnetite). The degree of solid solution possible increases with temperature, as indicated by the following data quoted from Greig et alia:

Temperature ° C.	Composition of Maximum Solid Solution	
	Fe_3O_4	Fe_2O_3
1075	92	8
1200	87	13
1388	75.5	24.5
1452	70	30

The ex-solution texture bears some resemblance to that resulting from the replacement of magnetite by hematite (martitization) during either hypogene or supergene oxidation of magnetite, but there are distinctive points of difference. In the ex-solution intergrowths the hematite lamellae are evenly distributed through the magnetite in blades of uniform size, and there is no concentration of the hematite at the crystal margins, or in patches or along fractures, whereas with oxidation of the magnetite, the alteration to hematite proceeds from the margins, crystal boundaries and fractures into the cores of the crystals, often giving rise to a rim of hematite that extends irregularly into the magnetite crystal. Natural occurrences of such intergrowths appear to be rare, and the writer is not aware that they have been recorded previously.

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[1] Greig, J. W., Posnjak, E., Merwin, H. E., and Sosman, R. B., *Am. Jour. Sci.*, **30**, 239–316 (1935).

Of the three to be recorded here, one occurrence is a pebble about 1 cm. across from a river gravel in the Cairns district of Queensland, Australia; the other two occur as grains in beach sands at the Vunda River and at Lautoka, both on the island of Viti Levu, Fiji. The Cairns specimen consists of a single waterworn crystal. The proportions of magnetite to hematite in the intergrowth (Fig. 1) have been measured micrometrically and are about 80:20, which from Greig's data quoted above, would indicate that the crystal originated at a temperature of about 1300° C. The source of the crystal is unknown, it being found in a concentrate supplied by a prospector in the Cairns district.

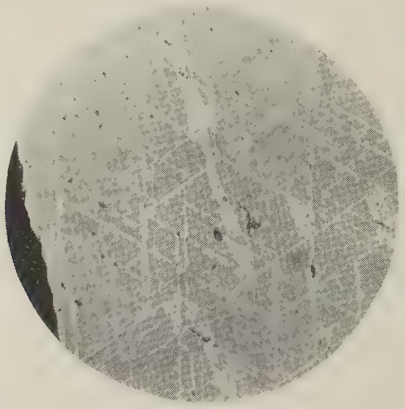

Fig. 1. Ex-solution intergrowth of hematite lamellae (white) in the (111) planes of magnetite (grey). × 40. Detrital crystal, Cairns district, Queensland.

In the other two occurrences intergrowths of this type, on a much finer scale, form grains up to 1 mm. across, which are a component of magnetite beach sands occurring in some volume on the south-eastern coast of Viti Levu. The relative proportions of magnetite to hematite vary from grain to grain, and could not be measured accurately, but are estimated to be about 85 parts of magnetite to 15 of hematite for both Vunda River and Lautoka, indicating a temperature of formation for these grains of about 1200° C. These beach sands are almost certainly derived from the volcanic rocks, chiefly andesites, of Viti Levu. In both sands magnetic minerals constitute more than 90 per cent of the total weight. The magnetic minerals are chiefly unoxidized magnetite, and the magnetite-hematite intergrowths. The intergrowths are more abundant in the Lautoka sand than in the Vunda River sand. The non-magnetic minerals present are chiefly augite, with occasional grains of hornblende, olivine, hypersthene, biotite, quartz and feldspar.

The temperatures of formation indicated for these mineral intergrowths are unduly high for igneous rocks, and this suggests that in the natural processes giving rise to such intergrowths some additional factor enters to permit such solid solution to exist at temperatures lower than those found in the laboratory studies of Greig and his associates.

MAGNETITE CRYSTALS FROM COPPER CONVERTER

R. S. Young and A. Golledge,
Rhokana Corporation Limited, Nkana, Northern Rhodesia,

AND

Miss H. J. Grenville-Wells,
Diamond Research Laboratory, Johannesburg, South Africa.

When one of the copper converters in the smelter of Rhokana Corporation at Nkana, Northern Rhodesia, was taken out of commission for relining recently, a small mass of black crystals was found in the bottom of the converter. Such an occurrence had never been observed before by the operating staff, many of whom have had a lifelong experience in the copper industry, and the crystals were turned over to us for examination. Figure 1 illustrates their general appearance, showing the growth of parallel partial crystals in the direction of the crystallographic axes.

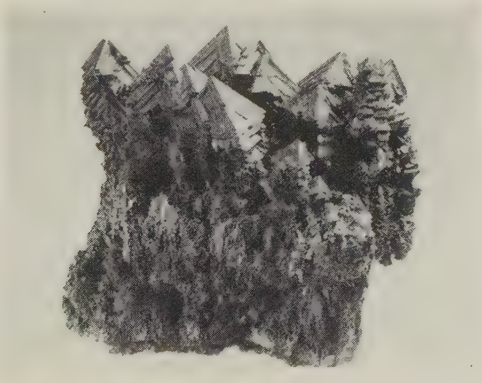

Fig. 1

The crystals were black, octahedral, magnetic, with a hardness of approximately 7 and a specific gravity of 4.2. Chemical analysis gave the following result:

	%
SiO_2	7.24
Al_2O_3	3.62
CaO	1.37
MgO	1.50
Cu	6.56
Co	5.28
S	0.22
Fe	51.56

Bearing in mind the temperatures, oxidizing conditions, matte and slag formations in copper converters, with particular reference to Rhokana conditions (2), it is probable that the composition of these crystals is the following:

	%
$3Al_2O_3 \cdot 2SiO_2$	5.0
$CaO \cdot SiO_2$	2.8
$MgO \cdot SiO_2$	3.8
Cu_2S	1.1
CuO	7.1
Co_2O_3	7.4
$FeO \cdot SiO_2$	4.6
Fe_3O_4	68.6
	100.4

The crystals apparently consist of approximately two-thirds magnetite, with the remaining constituents present as impurities or solid solutions.

A surprising feature of our *x*-ray examination was shown by the complete correspondence of the powder photograph of the crystal with a standard photograph of reagent-grade magnetite. There was no indication of any variation in lattice spacing from the values for pure magnetite. This was unexpected, in view of the lower specific gravity for this substance than the value of 5.16–5.18, quoted in mineralogical texts (1) for magnetite. It would be anticipated that the absence of distortion in the lattice would have indicated a specific gravity very similar to that of pure magnetite.

It is well-known, of course, that a low temperature and insufficient silica results in the formation of magnetite in basic copper converters, but this is always an amorphous layer practically indistinguishable from ordinary converter slag. The occurrence, under these conditions, of large crystals of magnetite, which possess the fundamental magnetite structure, though carrying nearly one-third impurities, is, we believe, quite unusual.

References

1. Dana, E. S., and Ford, W. E., Dana's Textbook of Mineralogy, New York, J. Wiley and Sons (**1945**).
2. Young, R. S., Cobalt, New York, Reinhold Publ. Co., (**1948**).

Esper S. Larsen, Jr., Professor of Petrography at Harvard University since 1923, retired July 1, 1949, and is now residing at 2029 North Kentucky Street, Arlington, Virginia. Dr. Larsen is doing special work for the U. S. Geological Survey. He also has quarters at the U. S. National Museum in Washington, D. C., where he will continue to carry on his own research.

Correction

The dispersion of sengierite as recorded in *Am. Mineral.*, **34**, 112 (1949) should read "$r<v$."

THE MOORE COUNTY METEORITE: A FURTHER STUDY WITH COMMENT ON ITS PRIMORDIAL ENVIRONMENT

H. H. Hess and E. P. Henderson

Errata

Page 495. Table 1, "Moore City" change to "Moore County."
497. Fig. 1, "augite lamellae in pigeonite are parallel to {100} plane," should be changed to "{001} plane."
499. Table 4, optic plane of hypersthene E given as "|| {010}" should be "|| {100}."
502. Line 16. Change "form" to "from."

BOOK REVIEWS

SEDIMENTARY ROCKS, By F. J. Pettijohn.

In this imposing and useful work Dr. F. J. Pettijohn, Professor of Geology at the University of Chicago, has attempted to encompass the fields of sedimentary petrology and petrography, rather than that of sedimentation. He succeeds to the extent that the volume will undoubtedly, in a short time, become one of the outstanding textbooks and reference works in its chosen field. Albeit the book lacks competition, nevertheless it develops a powerful summary of the properties, characteristics, and origins of sedimentary rocks, an orphan group that has long suffered the general neglect of petrologists.

The book is the seventh in the Geoscience Series published by Harper and Brothers and edited by Carey Croneis. It contains 526 pages in 15 chapters, 131 figures, 40 plates, 139 tables, and both an author and a subject index. The price is $7.50. One of the outstanding features is the profusion of excellent and pertinent illustrations that it contains. For the first time in a textbook the plates have been reproduced by the collotype process, which has provided results of unusual clarity. The 104 photomicrographs are particularly aptly chosen to illustrate in effective detail microscopic textures and structures, some of which are shown for the first time in a text of instructional character. The 40 other photographs, of handspecimens and outcrops, have likewise been carefully selected and prepared.

A short introductory chapter is followed by one on textures. From the ideal standpoint the arrangement of subject material might well have been initiated with the section on composition, for to discuss the arrangement and interrelations of material particles it is desirable to know first of what those particles consist. Under texture are included discussions of size, size frequency distribution, textural classifications, size analysis interpretation, shape, roundness, grain surfaces, fabric, packing, porosity, permeability, and nonclastic textural features. This is by many pages the largest chapter in the book (73 pages). Indeed the descriptive minutiae of textural analysis into which it delves foreswears somewhat the statement in the editor's introduction that the writer "regards this volume as an elementary treatment."

The chapter on composition treats first the chemistry and then the mineralogy of sedimentary rocks and closes with a brief discussion of radioactivity in sediments. It is strange to see that bauxite apparently is given status as a true mineral (table 29, p. 107), whereas limonite is used correctly, i.e., in quotation marks, in the same table. As discussed in the 7th edition of the Dana System on page 667, bauxite is a mixture containing several aluminous minerals. Under properties to be employed in distinguishing quartz from feldspar (p. 93) noteworthy omissions are the recognition of feldspar by its common turbid alteration and quartz by its clarity and "trains" of minute inclusions. In table 31, p. 110, a description of the carbonate minerals, twinning is stated to be absent in dolomite.

Sedimentary structures described in chapter 4 are subdivided into inorganic and organic, the former further into mechanical and chemical structures. Outstanding parts of this chapter include a thorough discussion of bedding and of the petrology of fossils. There follows a short chapter on color, which contains among other things, a summary of prevailing thought on red beds and their origin. According to Pettijohn, they "may originate under intermittently rainy, subarid, or arid climates without any close relation to temperature. They are typically fluvial or pluvial deposits upon the land, though to a limited extent they are fluviatile deposits coming to rest on the bottom of a shallow sea" (pp. 173–174). No mention is made in this section of such features as the color mottlings of carbonate rocks produced by partial dolomitization or of secondary concentric color bands formed in joint blocks in sandstones.

Chapter 6, on the classification of sedimentary rocks, begins with synopses of Grabau's and Krynine's classifications and concludes with an equitably restrained treatment of the graphic representation of sedimentary rocks by means of five compositional variables: M, stable primary detrital minerals, commonly quartz; N, stable secondary detrital minerals, usually clay minerals; X and Y, chemical components, such as carbonates and silica; and Z, any other nonclastic constituent, perhaps carbon. By means of such a scheme and its applications to 2-, 3-, and 4-component diagrams, it is believed that 95% of all sedimentary rocks can be represented adequately.

Next follows a group of five chapters, each describing a group of related rock types: conglomerates and breccias, sandstones, shales and argillites, limestones and dolomites, and non-clastic sediments. In this section probably lies the main strength of the book, for the descriptions of rock compositions and textures, as well as the discussions of their origins, are pellucid and coherent. Some rocks, for example, graywacke, are adequately treated probably for the first time. The controversial literature on these rocks is critically examined and distilled to dovetail with the facts of their occurrence and composition. Throughout the descriptive chapters are presented many new data, garnered through years of careful observation.

The final group of four chapters is concerned with processes: weathering, transportation, deposition, and lithification and diagenesis. The author in his preface states "... much of what is ordinarily considered 'sedimentation' is omitted. Many of the transient phenomena ... leave no record and can best be left out." This restriction probably enhances the value of the book, for it leaves more space for descriptions of the rocks themselves, with which the geologist is required to deal. The reviewer is in complete accord with Professor Pettijohn's declaration that in sedimentary rocks "thin-section studies must be the main basis for investigation rather than the exception."

Like all first editions, the book has defects, none of them serious and some, no doubt being rooted in the training and inclinations of its reviewer. A slight lack of balance is apparent, due possibly to the author's particular devotion to specialized aspects of his subject. The part on analytical methods applicable exclusively to unconsolidated materials seems excessive, especially in view of its limited usefulness. Some features and types of sedimentary rocks are discussed not at all or but inadequately; to name some examples: oil shales and kerogen, bauxite, vanadiferous phosphatic rocks, bentonite, and dolomitization. Typographical and proof errors are, of course, almost impossible to eliminate entirely, but the book appears to have a relatively large share. Some of those noted in a cursory hunt are: p. 77, A. J. Eardley reference is listed in the author index as appearing on p. 75; p. 106, G. Palache for C. Palache in the footnote; this error also appears in the author index; nor is the edition number given for the Dana System; p. 265, alternation for alteration; p. 341 maybe for may be; p. 354 phosphorous for phosphorus; and p. 376, Weyland for Wayland.

These defects are, in the main, minor and do not seriously detract from the general high standard of the book. Professor Pettijohn is to be congratulated on producing in its initial edition a quality work of fundamental importance to sedimentary petrologists. It is a book that most petrographers will wish to acquire after perusal and to peruse again after acquisition.

E. Wm. Heinrich
University of Michigan

RADIOACTIVE MEASUREMENTS WITH NUCLEAR EMULSIONS, By Herman Yagoda.

There is much of interest to mineralogists and crystallographers in "Radioactive Measurements with Nuclear Emulsion" by Herman Yagoda. Other parts of this 356-page book are directed toward physicists, biologists, chemists, and metallurgists. Because of relatively recent improvements in the development of special emulsions, the photographic process is once more proving valuable for recording and investigating radioactive emanations. The author has described the techniques and summarized their application in the various fields. In the preface he notes that every basic advance in our knowledge of radioactivity, such as the discovery of protons from radioactive decay or the recording of both light and heavy mesons, has been brought about through photographic detection methods.

The initial chapter opens with a historical review of the process of photographic nuclear particle detection and is followed by sections that discuss chemical reactions with emulsions, emulsion effects due to phosphorescence, to hydrogen peroxide produced, for example, by the oxidation of freshly abraded metal surfaces in moist air, to chromic acid, and to pressure. Other parts of this chapter deal with the nature of the image produced and of the autoradiographic mechanism. In chapter two the photographic and scintillation methods are compared. Of special importance to mineralogists are those parts of chapter 3 dealing with preparation of polished pieces of radioactive minerals, the mechanics of image production, and the techniques of image examination.

Then follow two chapters on the patterns produced by alpha particles on nuclear emulsions and the quantitative aspects of such patterns. The parts of the book that deal specifically with the use of the autoradiograph technique in mineralogy and crystallography are found in chapter 7 and in the first half of chapter 8. Sample topics treated here include determination of the uranium and thorium contents of minerals, a discussion of radiocolloids in geochemistry, discovery of radioactive minerals grains, and detection of rock radioactivity (1000 hours exposure). Data on the growth of crystals can be secured by mixing traces of radioactive ions in the mother solution and periodically allowing the radioactive zones to register on nuclear emulsions. The internal structure of radioactive minerals also can be recorded, and intergrowths of minerals with different contents of radioactive elements or of radioactive and non-radioactive grains can be detected.

The remainder of the book, chapters 11 and 12, is of lesser importance to students of crystallography and mineralogy, although brief mention is made of the application of the records of beta radiation to crystal study and of autoradiographic studies of minerals activated by neutron bombardment.

The book concludes with a valuable bibliography of 656 references, including 20 by the author himself, and two appendices: (1) Range-energy relations in Ilford nuclear research emulsions and (2) Atomic constants and conversion factors.

This volume represents the first published compilation of theoretical and technical information on methods of studying and measuring radioactive emanations by means of emulsions of the nuclear type. As such it should prove a valuable source book to scientists employing these devices and stimulate their further and wider application. The book is clearly and simply written. Individual chapters are somewhat heterogeneously organized, alternating between sections on practical technique and portions on theory, which leads to lack of continuity. The 75 figures, both line drawings and half-tone reproductions, are clear and pertinent. John Wiley is the publisher, and the cost is $5.00.

E. Wm. Heinrich
University of Michigan

REPORT OF THE COMMITTEE ON THE MEASUREMENT OF GEOLOGIC TIME, 1947–1948, by John Putnam Marble, Chairman. Presented for publication to Division of Geology and Geography, National Research Council, March 1949. Price $1.00. 77 pages.

This is the tenth mimeographed report of the Committee on Measurement of Geologic Time. The first report was issued in September 1936. Alfred C. Lane served as Chairman of the Committee of the first eight reports while the ninth and tenth were prepared under the chairmanship of John Putnam Marble. Some idea of the scope and character of the last report may be gained from a glance of the Contents with its six main headings, characterized as "Exhibits" which are enumerated below.

Contents

In Memoriam: Alfred Church Lane, 1863–1948
Summary Report of the Committee on the Measurement of Geologic Time for 1947–1948, by John Putnam Marble, Chairman
Supplementary reports, presented as Exhibits:
Exhibits:
A. Report from Dr. Arthur Holmes, University of Edinburgh
B. The Necessity for Different Values for the Ratio Pb/U of the Crust and the Rest of the Planet, by Sr. Dn. Dr. Juan Manuel López de Azcona (translated by A. H. Marble and J. P. Marble)
C. Review of Work in Japan, by John Putnam Marble
D. Archaeological Ages by Natural Radiocarbon Content, by Dr. W. F. Libby, with Comments by R. F. Flint
E. Preliminary Report on Determining the Age of Rocks by the Lead-Uranium Ratio of Zircon, Apatite, and Sphene from the Rocks using Alpha counting and Spectrographic Methods by E. S. Larsen, Jr., N. B. Keevil and H. C. Harrison
F. Annotated Bibliography of Articles Relating to the Measurement of Geologic Time compiled by J. P. Marble
List of Available Reports of the Committee

Anyone interested can obtain a copy of this Report by payment by check, draft or money order drawn in favor of the National Academy of Sciences, but mailed with order to the Division of Geology and Geography, National Research Council, 2101 Constitution Ave., N. W., Washington 25, D. C. Copies of the annual reports of the same Committee for the years 1935–36, 1936–37, 1937–38, 1938–39 and 1940–1941 available without charge; for 1941–42, 1942–43 at 50¢ each, and 1943–46, 1946–47 at $1.00 per copy. Complimentary copies (1 each) of these reports (while available, and unless previously sent) can be furnished to Libraries of educational institutions.

W. F. H.

DAS BESTIMMEN DER MINERALIEN, by Alexander Köhler, pp. v+150, 23 illustrations, octavo. Springer-Verlag, Vienna, 1949.

In these tables an attempt is made to combine the use of the optical constants and newer chemical methods, as developed by Feigl and Leitmeier, with the physical and chemical properties which can be readily determined at sight or by simple methods.

The author, who is professor of mineralogy at the University of Vienna, expresses the belief that these tables are superior to those of Weisbach-Kolbeck and Fuchs-Brauns which have long been in successful use. Eight pages are devoted to a brief discussion of the various physical properties, which are easily recognized or determined. In 20 pages blowpipe and the Feigl-Leitmeier chemical reactions are described and summarized. Simple optical determinations are very briefly mentioned in less than 4 pages. An outline of the procedure to be followed in using the tables, and 23 crystal drawings and diagrams of the extinction angles of some of the feldspars and members of the hornblende and augite groups conclude the first portion of the book, which comprises 41 pages.

In the tables, which cover 104 pages, minerals are arranged in groups according to luster, color, and increasing hardness. Streak, crystallization, and other diagnostic properties are listed, as well as the mineral associates and occurrences.

These tables will undoubtedly find considerable use among students and others competent in the German language.

Edward H. Kraus

COPPER IN CALIFORNIA (1948), by the State Division of Mines, 429 pages, accompanying map pocket, *Bulletin 144* of the Division of Mines publications.

Bulletin 144, entitled Copper in California, was recently released by the California Division of Mines and should prove of considerable interest to mining engineers, geologists, and mineralogists. Much of importance has occurred, both economically and geologically since the last copper publication, Bulletin 50, now out of print.

While no specific publication has been issued by the Department strictly upon the subject of copper for a number of years, the regular bulletins dealing with mining generally have devoted much attention to the activities of the copper mining industry. However, this information is not always readily available, and Bulletin 144 tabulates all previous publications, and records pertinent data on each copper property.

This new bulletin is divided into three parts, and is accompanied by an elaborate series of maps, the latter being in a specially-bound map pocket, which is separate from the printed volume. Part 1 is devoted principally to a study of the noted California Foothill Copper Belt; Part 2 affords a comprehensive presentation of marketing and metallurgical factors as related to the complex copper-bearing ores, while Part 3 summarizes the data upon copper production, discusses generally the distribution, mineralogy, and geology of California copper deposits, and includes an excellently tabulated list of California copper occurrences.

The major portion of the volume consists principally of contributions by the United States Geological Survey and the Bureau of Mines, based upon strategic mineral investigations. One of the most valuable features of the volume is a carefully selected and detailed bibliography; the index is likewise exceedingly complete. It will stand as a milestone of progress in presenting the history, geology, economics and future of the California copper occurrences. Appearing as it does, in California's Centennial year, adds interest to the volume.

J. B. Nichols

PROCEEDINGS OF SOCIETIES

MINERALOGICAL SOCIETY (LONDON)

A meeting of the Society was held Thursday, June 23, 1949, in the apartments of the Geological Society of London, Burlington House, Picadilly, W. 1 (by kind permission).

The following papers were presented:

(1) On the occurrence of neptunite and eudialyte in quartz-bearing syenites from Barnavave, Carlingford, Ireland.

By Dr. S. R. Nockolds.

The rare minerals neptunite and eudialyte, both previously unrecorded from the British Isles, are found as accessory constituents in peralkaline syenites at Barnavave, composed essentially of potash feldspar with varying amounts of quartz and ægirine-augite and minor amounts of sphene, wollastonite or pectolite. The syenites occur only as veins in limestone and are believed to represent original granite magma which has been desilicated with loss of Si, some Al and a little Na.

(2) Correlation of the Mohs's scale of hardness with the Vickers's hardness numbers.

By Mr. E. W. Taylor.

It has been found possible to measure the hardness of minerals by applying a diamond indenter under light loads. The impressions so obtained, although minute, may be regarded as an index to the hardness of the material, as is the case with metals and alloys. An attempt has been made to obtain the relative, if not the absolute, hardness figures for nine of the ten minerals included in Mohs's scale, and to express them by means of Vickers's hardness numbers.

(3) An X-ray examination of a sample of pure calcite and of solid solution effects in some natural calcites.

By Dr. K. W. Andrews (communicated by Dr. G. F. Claringbull).

"Specpure" calcium carbonate gave parameter values of $a = 6.3748 \pm 0.0005$ Å., α 46.08°, which are compared with previously reported values for calcite. An x-ray examination of nine natural calcites, of which seven are present in low-grade iron ores, reveals changes in inter-planar spacings which can be largely accounted for as being due to solid solution replacement of calcium by manganese. It is thought that in the natural calcites examined there is a residual solid solution content of some other carbonate or carbonates (probably of iron and possibly of magnesium) even when no manganese carbonate is present.

(4) Analytical notes II. The "ferrous iron" and silica determinations in rocks and minerals.

By Dr. M. H. Hey.

The tedious duplication of all the main determinations in a rock or mineral analysis may usually be avoided by utilization of some of the solutions and residues normally discarded; thus by a slight modification of the method of Meier and Stuckert, silica may be advantageously determined in the residue from the Lawrence Smith alkali determination. The determination of the state of oxidation by solution in $HF+HCl+ICl$ and titration with KIO_3 is applicable to a wide variety of rocks and minerals and has notable advantages if the percentage of FeO is very low.

(5) EIGHTEENTH LIST OF NEW MINERAL NAMES.

By Dr. L. J. Spencer.

(*Titles and abstracts submitted by G. F. Claringbull, General Secretary*).

NEW MINERAL NAMES

Pennaite, Giannetite

DJALMA GUIMARÃES, the circonium ore deposits of the Pocos de Caldas plateau, Brazil, and zirconium geochemistry. *Estado Minas Gerais, Inst. Tecnologia Industrial, Bol. 6,* 1–79 (1948) (in English 43–79).

Pennaite is described as a yellow to light brown, prismatic to acicular mineral. It is biaxial, positive, with $\beta=1.70$, $\gamma-\alpha=0.044$, 2V 25°, $c\wedge Y=13°$. It is pleochroic with X dark yellow (p. 57), soiled yellow (p. 61), Y grayish-yellow, Z bright yellow (p. 57), yellowish-brown (p. 61). It shows polysynthetic twinning and may be triclinic. "The presence of Zr, Ti, Ca, Fe and Mn was ascertained. Pennaite could not be freed for testing except in minute amounts and for approximate figures only. Constituent elements gave the following rough averages: SiO_2 40–45, TiO_2 8–10, ZrO_2 4–6, FeO 10–15, MnO 3–4, CaO 10–15, Na_2O 10–12, Cl 2–3%." Soluble in HCl. Spectrographic traces of Ta are present.

Giannetite occurs in colorless to pale yellow prismatic crystals. It is apparently triclinic and shows perfect cleavage on (100), indistinct and irregular cleavage on (010) and (001). The crystals are twinned, mostly along the (100) plane. It is optically biaxial, positive, with $\alpha=1.663$, $\beta=1.664$, $\gamma=1.675$, all ± 0.002, 2V 30°, $c\wedge Y=22°$. Spectrographic study of a few grains showed the presence of Si, Ti, Zr, Mn, Fe, Ca, and Na, with traces of Ta and rare earths absent. Since the mineral could not be separated, analyses were made of the material dissolved in acid from two rocks. These yielded totals of 4.17 and 3.68%, respectively, from which were subtracted 1.72 and 1.59% of nepheline, apatite, magnetite, and zeolite, whose amount was known from the mode of the rock. By recalculation to 100%, this gives for the composition of giannetite: SiO_2 40.0, 36.3; ZrO_2 8.35, 8.4; TiO_2 8.0, 9.0; Fe_2O_3 2.45, 2.5; MnO 9.7, 9.1; CaO 22.3, 14.95; Na_2O 5.6, 17.0; Cl 3.4, 3.1%.

The two minerals occur in alkalic rocks (foyaites, phonolites, tinguaites, lujavrites). They are associated with eudialyte, catapleite, aegirite, fluorite, sanidine, nepheline, and sodic amphibole. Both minerals are apparently hydrothermal alteration products of aegirite.

NAMES: The minerals are named for José Moreira do Santos Penna, chief of the Instituto de Tecnologia Industrial of Minas Gerais, and for Dr. Americo René Gianneti, civil and mining engineer, Secretary of Agriculture, Industry and Commerce of Minas Gerais.

DISCUSSION: Further study, especially chemical analyses and x-ray work, is needed. The minerals might be related to hiortdahlite.

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A FEW OUTSTANDING SPECIMENS FROM WARD'S STOCK

These good quality specimens are from both old and new localities. They include both rare and common species.

Apatite, var. **Hydroxylapatite.** Hollysprings, Georgia. Large yellow crystalline masses in chlorite schist. 6 x 12", **$7.50**

Autunite. Palermo Quarry, Groton, New Hampshire. A choice specimen with good crystals and crystalline masses on feldspar. An excellent fluorescent specimen. 4¼ x 6½", **$7.50**

Berzeliite. Långban, Sweden. Rich, yellow masses in dolomite. An attractive specimen, 6½ x 7 x 3½", **$22.50**

Braunite. Långban, Sweden. Black crude crystals with schefferite. 3 x 4", **$6.00**

Caryinite. Långban, Sweden. A lead bearing arsenate of calcium, sodium, magnesium and manganese, closely related to berzeliite. Rich brown masses with hedyphane, braunite and richterite, 3½ x 4¼", **$20.00;** brown xline with braunite and richterite, 4 x 5 x 4", **$25.00**

Huebnerite. Near Henderson, Vance County, North Carolina. The huebnerite occurs as rich xline brown cleavages in quartz with fluorite, scheelite and rhodochrosite. 5 x 8¾ x 3½" (nearly 10 lbs.), **$45.00**

Magnetite. North of Bass Lake, Mongowin Twp., Espanola Area, Ontario. A pure radiating mass from a serpentine vein, 3½ x 5", **$5.00**

Pollucite. Varuträsk, Sweden. Massive with rose pink rubellite, 3 x 4", **$7.50**

Sylvanite. Moon and Anchor Mine, Cripple Creek, Colorado. Crystallized and crystalline in quartz. 1¾ x 3", **$12.50**

Xenotime. Arendal, Norway. A nearly pure mass 2⅞ x 3 x 2¼", **$65.00**

All prices are F.O.B. Rochester, N.Y.

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